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**SNAP-23A PROGRAM
PHASE I
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM
QUARTERLY REPORT NO. 4**

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Report No. MMM 3824-0017
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**SNAP-23A PROGRAM
PHASE I****THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM****QUARTERLY REPORT NO. 4**

October 1, 1967 through December 31, 1967

Prepared by
J. V. Wachenheim
Project Engineer

Approved by
D. D. Schley
SNAP-23A
Program Manager

Issued by

SPACE AND DEFENSE PRODUCTS
MINNESOTA MINING AND MANUFACTURING COMPANY
ST. PAUL, MINNESOTA 55119

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U.S. Atomic Energy Commission RDT Site Office, 3M Company 2501 Hudson Road Space Center, Building 551 St. Paul, Minnesota 55119 Attn: John J. Stefano	1
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FOREWORD

The Minnesota Mining and Manufacturing Company (3M Company), as prime contractor to the United States Atomic Energy Commission under contract AT(30-1)-3418, designed, developed, fabricated and tested the SNAP-23 60-watt mockup radioisotope power supply system. The basic SNAP-23 Program was directed toward the development of high performance, reliable thermoelectric converter modules, using segmented thermoelectric legs, having a five-year design life.

As a result of the advancements made in the application of segmented thermoelectric legs during the preliminary SNAP-23 effort, the AEC initiated a follow-on development program designed to advance the SNAP-23 technology into a series of technically improved and economically competitive radioisotope power systems in the 25- and 100-watt power ranges with a ten-year design life objective.

The SNAP-23A development effort is directed toward the design, fabrication, and test of a thermoelectric converter design to be used as a component in the 60-watt SNAP-23A Terrestrial Radioisotope Power Supply System. This document reports progress for this effort from the period 1 October through 31 December 1967.

The 3M Company Converter Development Program is being performed under AEC contract AT(30-1)-3824, in conjunction with the SNAP-23A system contractor, Westinghouse Astronuclear Laboratory (WANL). While the converter development program is directed toward the development of a 60-watt converter and conceptual designs for 25- and 100-watt converters, major emphasis will be concentrated on development of a design for thermoelectric couples which will perform reliably over a ten-year design life.

The specific requirements of the Phase I SNAP-23A development effort are:

- Design, develop, fabricate and test 60-watt(e) converters
- Prepare conceptual designs for 25- and 100-watt(e) converters

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SECTION 1.0

SUMMARY

SECTION 1.0

SUMMARY

During this quarter, fabrication and final assembly of the first Experimental Mockup Converter was completed. The unit was placed on test for a nominal 500-hour period after which shipment will be made to Westinghouse for system integration early in the next quarter.

Power output of the first 60-watt converter was below the predicted value. An investigation was started to determine the cause. As an interim measure, plans were made to change the basic thermocouple design configuration to include bonded type P-legs in Experimental Mockup Converter No. 3. This has undergone extensive testing in the SNAP-23A 10-Couple Module Test Program and in the related SNAP-21 Program, Contract AT(30-1)-3691.

Heat transfer improvements are required at the spherical cold electrode-to-follower interface in order to reduce temperature drop to the specification level of 30°F maximum. Two approaches have been investigated and have the required capability: use of indium foil at the spherical interface with existing aluminum hardcoated followers, and use of beryllium oxide followers. The first approach will be implemented in Experimental Mockup Converter No. 3, and the latter approach is under investigation for application on the Prototype Mockup Converters. Beryllium oxide material exhibits the ultimate combination of electrical resistance and heat transfer characteristics for the application.

Other significant highlights occurring during this period are summarized below:

- Experimental Mockup Converter No. 2 final assembly completed including installation of the outer case.

- Completion of thermoelectric material characterization of discrete segments was completed.
- Thermoelectric material numerical coefficients were both formulated and implemented into the converter design program and submitted to Westinghouse for use in their system computer code.
- The Post-Test Analysis Plan and Report document was issued.
- Fabrication and design of support equipment was completed including Process and Test Stations Nos. 1 and 2, Converter Shock and Vibration Fixture, and the Shipping Container.
- 3M and Westinghouse made a number of agreements relative to establishment of the Prototype Mockup Converter and System interface. The present design has sufficient capability to allow commonality between the Experimental and Prototype Mockup designs in the following areas: physical interface dimensions, internal diagnostic instrumentation, instrumentation location where location is critical to interfaced component configuration, preliminary hot and cold side thermal conditions, and electrical performance requirements.

SECTION 2.0
TASK I—PROGRAM MANAGEMENT

SECTION 2.0

TASK I-PROGRAM MANAGEMENT

2.1 LIAISON

Extensive coordination and liaison activities were performed throughout the reporting period with Westinghouse Astronuclear Laboratory (WANL) with respect to the physical interface of the fabricated Experimental Mockup Converter No. 1 and its performance data.

3M and Westinghouse liaison activities during the quarter were concerned with the following items:

- Material deviations and Westinghouse/3M joint dispositions on interfacing components.
- Thermoelectric Material Recharacterization.
- Joint review of respective test plans.
- Performance data of Experimental Mockup Converter (EMC) No. 1.
- Design resolutions concerning integration of EMC No. 1 with SNAP-23A system resulting from low power output and thermal mismatch due to large cold end heat transfer drop.
- Review and preliminary reschedule of the design base and technology selection controlling the design of the Prototype Mockup Converter (PMC).

2.2 DOCUMENTATION AND REPORTS

The following documents were published during the fourth quarter.

- Quarterly Report No. 3, MMM 3824-0013, covering the period 1 July 1967 through 30 September 1967.
- Monthly Reports – October 1967, Report No. MMM 3824-0014, November 1967, Report No. MMM 3824-0016.
- Post-Test Analysis Plan and Report, MMM 3824-0002.
- Experimental Mockup Converter Test Plan and Procedures, 3M-39-IPP-105 dated 22 November 1967.
- Performance and Design Requirements for the Experimental Mockup Converter, 3M-39-IPP-94 dated 1 November 1967.
- Design Review Report – Experimental Mockup Converter, R003 dated 2 November 1967.

2.3 EFFORT PLANNED FOR THE NEXT QUARTER

Major schedule efforts for the next reporting period include:

- Pack and ship Experimental Mockup Converter (EMC) No. 1 to Westinghouse for system integration.
- Complete final assembly and processing for EMC No. 2.
- Conduct shock and vibration tests on EMC No. 2.
- Incorporate design changes into EMC No. 3.
- Complete final assembly and processing for EMC No. 3.
- Evaluation of EMC No. 3 initial performance.
- Design release of Prototype Mockup Converter (PMC) long lead piece parts.
- Preliminary design release of PMC couples and couple related hardware.
- Conduct Reliability review on 60-watt converter design.

SECTION 3.0

TASK II – 60-WATT CONVERTER DEVELOPMENT

SECTION 3.0

TASK II-60-WATT CONVERTER DEVELOPMENT

3.1 INTRODUCTION

The objective of this task is to design, develop, fabricate and test a thermoelectric converter which will interface with the SNAP-23A power supply system. As a component of the system, the converter is required to produce 60 watts under 10-year end-of-life (EOL) temperature conditions.

Under Phase I of this program, two distinct converter designs will be prepared. The design effort for the first of these, the Experimental Mockup Converter, was completed during the third quarter and Unit No. 1 was fabricated, processed, and short-term tested. Experimental Mockup Converter No. 1 will be delivered to Westinghouse for system integration early in the next quarter. Planning continued for the second converter; the Prototype Mockup Converter continued as discussed in paragraph 3.2.2. Efforts for converter support equipment are covered in paragraph 3.2.3.

3.2 DESIGN AND ANALYSIS

3.2.1 EXPERIMENTAL MOCKUP CONVERTER

3.2.1.1 Design Summary

Efforts this quarter consisted primarily of design details and engineering follow-up on design problems identified during assembly of Experimental Mockup Converters Nos. 1 and 2 and processing of unit No. 1

At the start of the quarter, assembly prints were issued along with the specifications necessary to build Experimental Mockup Converter No. 1. These specifications included ES (Engineering Specification) 1401 (TIG edge welding), ES 1402 (TIG pin welding), ES 1501 (converter processing). Military specifications covering soldering, spot welding and silver brazing were also called out. In addition to issuance of the above, the manufacturing shrink fit procedure for assembling the converter outer case to the thermopile, cold frame, and hot frame was reviewed and precautions to maintain engineering assembly dimensions were called out on the drawing.

The design of the power output header was such that a 16-gage copper wire could pass through it and be soldered leak tight. To provide a base in the output header pin for the soft solder, the manufacture of the header was requested to tin the interior of the Kovar pin. This soft solder tinning oxidized enough, so that when the copper output wire was moved after soldering, it broke the leak tight integrity. To resolve this problem the following revisions were added for converters, Nos. 2 and 3: (1) Header pin was nickel plated on inside of tube to provide a better soft solder base in output header pin that could withstand shrink fit temperature, (2) the already soft copper wire was annealed to provide still more flexibility after soldering, and (3) one-eighth inch out of output header, a flexible braid equivalent to 16-gage wire was used to complete the output termination. Test work was performed prior to this installation to determine its feasibility.

The initial design called for teflon covered wire in the area of the outer case side walls, and thermocouples from instrumentation headers to instrumentation receptacles. Because teflon was not available, fiber glass braid teflon impregnated covered wire was used on Converter No. 1. This material was unsatisfactory due to moisture absorption and poor abrasion characteristics. It was later replaced by bare thermocouple wire covered with teflon sleeving. Converters, Nos. 2 and 3, will use this configuration; and, where temperature permits, a nylon covered thermocouple wire will be used to eliminate the sleeving operation on bare wire.

After Converter No. 1 was built, it became apparent that additional support would be needed to secure the output wires. The wire from the output header and the wire to the receptacle are two separate wires so that the outer receptacle wire can be moved without disturbing the header wire. Each wire is separated by a securing nut. For Converter No. 2 a decision was made to lower the horizontal profile

of the output terminal. In this case the wire is not broken at the terminal as in No. 1. The output wire attached to couples, No. 1, 40, and 20, are brought out of the output header for about a 1/16-inch. They are then bent at right angles. At this point flexible hollow braid is brought over the output wire for 1/4-inch and soldered. This braid is brought up between two pieces of teflon with a metal strap for securing before going on to the receptacle. This design provides for a closer profile and compact attachment. In both cases shrinkable tubing is used around the wires.

Another revision made for Converters 2 and 3 based on experience gained in the assembly and processing of EMC No. 1 was rescheduling of attachment of the pressure transducer, gas sampling valve, and tubulation fitting until after the assembly shrink fit operation. Both the gas sampling valve and pressure transducer contain components that cannot withstand the temperatures reached during the shrink fit operation without damage; the tubulation fitting copper tube undergoes unnecessary oxidation.

3.2.1.2 Shunt Heat Loss

Shunt heat loss is determined by calculating the heat losses through the converter insulation. The initial SNAP-23A nominal design value for shunt heat loss* was based on data from the SNAP-23A parametric study which used the best insulation thermal conductivity values (k) available at that time. These included using the published thermal conductivity values for Min-K 1301 since the thermal conductivity value for powdered Min-K 1301 (major converter insulation) had not been determined.

As a result of a recent investigation by 3M Central Research Laboratories, thermal conductivities values for powdered Min-K 1301 have been determined and are presented in Figure 3-1 for both xenon and argon gas.

Table 3-1 gives the new nominal shunt heat loss values based on the new thermal conductivity values for both xenon and argon gas.

* 59.9 watts at EOL using Xenon Fill Gas

Figure 3-1. Conductivity versus Temperature for Powdered Min-K 1301, 1999 at 12.5 lbs/cu. ft.)

Table 3-1. Shunt Heat Loss Comparison for Xenon and Argon at EOL

Heat Loss Location	Heat Loss, Watts	
	Xenon	Argon
Insulation	35.1	41.2
Lower Cover	23.9	23.9
Upper Cover	12.1	12.1
Total	71.1	77.2

3 2.2 FABRICATION AND ASSEMBLY

During this quarter, processing of Experimental Mockup Converter No. 1 was completed (5 December) and the thermopile had been assembled, the outer case installed by shrink fitting, and the header pins with transition pieces sealed on Experimental Mockup Converter No. 2. Figure 3-2 shows a flow diagram for this assembly through processing. Figure 3-3 shows typical operations and stages of converter assembly, and the converter on the Process and Test Station.

Details of fabrication, assembly, and processing problems encountered during manufacturing efforts this quarter for Experimental Mockup Converters No. 1 and No. 2 are discussed in the following paragraphs. As can be noted in paragraph 3.2.2.2, experience gained and actions taken to date have all but eliminated problems incurred during assembly of Experimental Mockup No. 1 in assembly of Experimental Mockup Converter No. 2.

3 2.2.1 Converter No. 1

Final assembly of Converter No. 1 commenced on 10 October. A number of delays were experienced during assembly. Principal among these were:

1. The couple cold junction electrodes (Figure 4-1) were too stiff to allow proper couple seating. After this problem was found, the cold junction

Figure 3-2 SNAP-23A Converter Assembly Flow Diagram

b. Placement of Hot Junction Electrodes into Insulating Strip

a. Thermoelectric Couples in Associated Hardware

c. Placement of Thermoelectric Couples into Assembly Fixture

Figure 3-3. Experimental Mockup Converter No. 2 Assembly

d. Thermoelectric Couple Assembly Fixture

e. Locking Couples into Generator

f. Thermopile Assembly

Figure 3-3. Experimental Mockup Converter No. 2 Assembly (Cont'd)

h. Typical Header and Transition Terminals

g. Converter after Outer Case to Thermopile Shrink Fit Operation and Assembly of Top Cover

i. Converter on Process Station

Figure 3-3. Experimental Mockup Converter No. 2 Assembly (Cont'd)

electrode (jumper wire) design was investigated and changed as described in paragraph 4.3.1. The original couples were removed from the thermopile, and the unit was rebuilt using new couple assemblies.

2. A weld burn back (approximately 3/4-inch long) was experienced in the lower cover/hot frame weld as described in paragraph 3.5.1. The original weld schedule used the same sample to represent the lower cover/hot frame and the support cone/hot frame welds (Figure 3-18) since analysis indicated it was representative of both. However, although the sample was representative of both converter weld areas in the immediate area of the weld, the support cone/hot frame had a greater heat sink in the area beyond the immediate weld area than the lower cover/hot frame. This caused the initial setting to be excessive for the lower cover/hot frame weld. The setting was then readjusted and the weld finished. The finished weld was found to be within leak specifications when tested, and assembly proceeded.

For subsequent units new samples were made which give more precise representation of the lower cover/hot frame weld area. A new weld schedule was established from these samples as described in paragraph 3.5.1.

3. Difficulty was experienced in soldering the instrumentation wires to the stainless steel transition pieces at the headers (Figure 3-3 (h)) using rosin core flux. The initial development on test samples indicated that the instrumentation wires could be successfully attached using rosin flux; this type of flux is preferred because of less probability of header insulation contamination. However, it was found during assembly that a stronger flux was required to ensure a good joint every time. Eutectic No. 157 flux (acid base) was then used which required the development of a cleaning schedule to ensure the removal of the acid without damaging the headers. The procedure developed (paragraph 3.5.2) consisted of scrubbing with water and reagent grade acetone and then immediately blowing dry with dry nitrogen.

A study was conducted to improve the "external instrument wires to transition piece attachment method" for Experimental Mockup Converters

Nos. 2 and 3. This resulted in the present method which consists of the instrumentation wires being brought through a transition piece strain relief hole and tack welding on the opposite side.

Assembly of Converter No. 1 was completed the week of 13 November and processing began 17 November. Three major problems were encountered during processing. The first occurred at the end of the seat-in cycle.

The first problem was that the hot frame developed a leak in the weld burn back area (discussed previously) at the beginning of the 24-hour soak period. The converter was removed from the test station, and an evaluation of the weld (including X-rays) was made. A wet detergent bubble test pinpointed the leak area. It was on the inside at the base of the burn back area and appeared to be two points approximately 3/64th of an inch apart (possibly jointed). It was repaired by rewelding using stainless steel 308L filler metal.

The second problem was that the power output header hermetic terminal began to leak. This occurred after the hot frame weld repair, but prior to placing the unit back on the Processing and Test Station. This was repaired by resoldering and adding a terminal block on the converter upper flange to provide strain relief. The output wires were terminated at the terminal block, and a flexible cable was brought from this to the power output header. Addition of the terminal block to Experimental Mockup Converter No. 1 caused interference between the converter and the system radiator fins requiring rework of the upper fin areas by Westinghouse for system No. 1. The converter terminal block was redesigned for Experimental Mockup Converter units, Nos. 2 and 3. Thus, the converter can be mated to the system without interference.

The hermetic power output header used in Experimental Mockup Converter No. 1 lead through pins were initially tinned, but investigation of the problem described in the previous paragraph led to the conclusion that the tin burnt off during the converter assembly heat shrink operation. The output headers to be used on units, Nos. 2 and 3, have been revised to include nickel plating of the end of the tube. A test sample of the nickel plated power output header was tested by subsection to simulated heat shrink conditions. The solder joint was then evaluated and found to display good bonding and sealing properties.

The third problem was that the pressure transducer malfunctioned. The output curve was flat over the entire converter pressure range. The cause was determined to be a combination of improper handling, excitation during processing, and too hard a vacuum during processing. Although our intended environmental usage of the transducer was related to the vendor, no precautionary handling or environmental limitation information in regard to subjection or operation was received until after additional inquiries were made by us during our investigation of the transducer failure. A temporary pressure gauge was added to the gas sampling tube to provide pressure readout data during converter manufacturing processing and initial verification testing. It was sealed off and removed prior to delivery to Westinghouse.

3.2.2.2 Converter No. 2

At the end of this reporting period, Converter No. 2 thermopile had been assembled, the outer case installed by shrink fitting, and the header pins with transition pieces sealed. No major problems had been encountered at the end of the reporting period.

3.2.2.3 Converter No. 3

Fabrication of piece parts for Converter No. 3 is essentially complete and thermopile assembly is scheduled to start 22 January.

3.2.3 TEST

3.2.3.1 Short-Term Test

During the fourth quarter, Experimental Mockup Converter No. 1 was placed on short-term test. The test program consisted of two periods:

1. Initial performance verification period.
2. Stability conditioning period

Results of the initial performance verification are listed in Tables 3-2 through 3-6. Initial performance at various EOL and BOL operating conditions is shown graphically in Figures 3-4 through 3-7. Evaluation of EMC No. 1 performance in terms of experimental-to-theoretical ratios for instantaneous open circuit (Seebeck) voltage and internal resistance is shown in Table 3-7.

Nomenclature for Tables 3-2 through 3-6.

T_{oc}	Outer Case Temperature (°F)
T_{hf}	Hot Frame Temperature (°F)
T_c	Cold Junction Temperature (°F)
T_h	Hot Junction Temperature (°F)
V	Load Voltage (volts)
E	Open Circuit Voltage (volts- Instantaneous)
I	Load Current (amperes)
R	Total Resistance (ohms)
P	Power Output (watts)
P_{in}	Gross Power Input (watts)
Q_{loss}	Test Station Losses (watts)
Q_{in}	Net Power Input (watts)
η	Efficiency (percent)
T_{hr}	Elapsed Time (hours)
ΔT	Hot Side Temperature Differential (°F)

Table 3-2. EMC No. 1 Mapping Data – EOL Conditions

Parameter	Nominal Design Point	Off-Nominal Load Current	Off-Nominal Load Current	Short Circuit Conditions
T_{oc} (°F)	126	127	127	131
T_{hf} (°F)	934	995	890	859
T_c (°F)	173	174	176	182
T_h (°F)	900	965	857	826
V (volts)	23.0	36.0	12.0	0.001
E (volts-Int)	40.9	45.3	37.9	35.7
I (amps)	2.21	1.09	3.31	4.57
R (ohms)	8.10	8.53	7.82	7.81
P_{output} (watts)	50.9	38.2	39.7	0.00457
P_{in} (watts)	864.0	864.0	864.0	864.0
Q_{loss} (watts)	32.8	—	—	—
Q_{in} (watts)	831.2	—	—	—
η (%)	6.12	—	—	—
T_{hr}	43.4	47.0	51.0	54.0
Q_{loss} , Q_{in} , and η raw data not evaluated for off-design conditions				

Table 3-3. EMC No. 1 Mapping Data – BOL Conditions

Parameter	Nominal Design Point	Off-Nominal Load Current	Off-Nominal Load Current	Short Circuit Conditions
T_{oc} (°F)	136	138	138	142
T_{hf} (°F)	1120	1086	1065	1020
T_c (°F)	192	194	198	202
T_h (°F)	1083	1052	1028	1016
V (volts)	25.0	16.0	8.0	3.0
E (volts-Int)	52.5	50.5	49.0	48.0
I (amps)	2.90	3.70	4.40	4.83
R (ohms)	9.48	9.32	9.32	9.32
P_{output} (watts)	72.5	59.2	35.2	14.5
P_{in} (watts)	1100.0	1100.0	1100.0	1100.0
Q_{loss} (watts)	45.1	—	—	—
Q_{in} (watts)	1054.9	—	—	—
η (%)	6.87	—	—	—
T_{hr}	66.5	70	73	76
Q_{loss} , Q_{in} , and η raw data not evaluated for off-design conditions				

Table 3-4. Experimental Mockup Converter No. 1 Initial Performance
Verification Design Current Point - EOL

T_{oc}	123°F
T_{hf}	928°F
T_c	172°F
T_h	901°F
V	20.9 volts
E	41.0 volts
I	2.50 amps
P	52.3 watts
P_{in}	88.0 watts
Elapsed time	63.0 hours
ΔT	21°F Hot side axial differential

Table 3-5. EMC No. 1 Test Data for EOL Off-Design Cold
Junction Temperatures (Nominal EOL $T_c = 174^\circ\text{F}$)

Parameter	Cold ** Junction Temperature of 153°F	Cold ** Junction Temperature of 193°F
T_{oc} ($^\circ\text{F}$)	103	148
T_{hf} ($^\circ\text{F}$)	928	930
T_c ($^\circ\text{F}$)	153	193
T_h ($^\circ\text{F}$)	899	901
V (volts)	23.0	23.0
E (volts-Int)	41.4	40.3
I (amps)	2.33	2.11
P_{output} (watts)	53.6	48.5
P_{in} (watts)	880.0	840.0
T_{hr}	58.0	60.9
ΔT^*	24	20

*Hot side axial differential

**Objective is to obtain performance data at two points approximately $\pm 20^\circ\text{F}$ off nominal design point for system integration purposes.

Table 3-6. EMC No. 1 Test Data for BOL Off-Design Cold Junction Temperatures (Nominal BOL $T_c = 191^\circ\text{F}$)

Parameter	Nominal Cold Junction Temperature	Cold ** Junction Temperature of 173°F	Cold ** Junction Temperature of 154°F
T_{oc} ($^\circ\text{F}$)	138	115	92
T_{hf} ($^\circ\text{F}$)	1118	1119	1120
T_c ($^\circ\text{F}$)	194	173	154
T_h ($^\circ\text{F}$)	1084	1085	1085
V (volts)	25	25	25
E (volts-Int)	53.6	54.3	55.1
I (amps)	2.63	3.06	3.18
P_{output} (watts)	73.3	76.5	79.5
P_{in} (watts)	1112	1136.0	1160.0
T_{hr}	128.5	130.5	135.0
ΔT^*	22	24	24

*Hot side axial differential

**Objective is to obtain performance data at two points approximately $\pm 20^\circ\text{F}$ off nominal design point for system integration purposes

Figure 3-4. Current-Voltage for SNAP-23A EMC No. 1-EOL

Figure 3-5. Current Voltage for SNAP-23A EMC No. 1 - BOL

Figure 3-6. Performance of SNAP-23A EMC No. 1-EOL

Figure 3-7. Performance of SNAP-23A EMC No. 2-BOL

A major portion of the stability conditioning period was completed during the final weeks of this quarter. However, evaluation of EMC No. 1 performance versus time is complicated by the fact that at the start of the stability conditioning period, one of six parallel electrical heaters in the heat source failed, resulting in an assymetric temperature distribution (radially) within the converter even after readjusting the input power. This precludes direct comparison of the stability conditioning period data with that obtained prior to the heater failure (146 hours elapsed test time).

Figure 3-8 represents graphically the performance of EMC No. 1 during the stability conditioning period. During the period, the converter was operated at as close to BOL conditions as possible ($T_{h \text{ avg}} = 1070 \pm 3^\circ\text{F}$, 1053 to 1100°F range; $T_{c \text{ avg}} = 191 \pm 3^\circ\text{F}$) under the allowable operating conditions (1100°F maximum on any hot electrode). Table 3-8 contains the stability conditioning period performance of EMC No. 1 in greater detail than the graphical representation of Figure 3-8.

To evaluate EMC No. 1 from an efficiency standpoint, a thermal analysis of the test station (described in paragraph 3.2.3.1 of Quarterly Report No. 3) was run to determine the amount of heat received by the converter. The results of the analysis for EOL and BOL design conditions are shown in Figures 3-9 and 3-10 along with a summary of the total fixture losses and converter efficiency calculations. It is believed the test station losses shown represent a minimum value since the analysis uses the Johns-Mansville thermal conductivity book values for Microquartz blanket insulation and the test station uses shredded Microquartz. No values are available for shredded Microquartz; however, because the losses represent only approximately 4 percent of the total heat input, even if the thermal conductivity values used for Microquartz were doubled (thereby doubling test station losses), it would increase the calculated converter efficiency by less than 0.25 percent.

Table 3-7. SNAP-23A EMC No. 1 Initial Performance Ratios
Experimental Value at EOL and BOL Design Conditions
Theoretical Value

	Seebeck Ratio		Resistance Ratio*	
	EOL	BOL	EOL	BOL
Thermopile	1.01	0.99	1.31	1.18
Typical N-leg	1.00	0.99	1.00	0.97
Typical P-leg	1.03	0.99	1.68	1.44

*Theoretical resistance includes no extraneous resistance allowance.

NOTE: Theoretical values are based on the new materials characteristics discussed in paragraph 4.2.2.

Table 3-8. SNAP-23A EMC No. 1 Stability Conditioning Period Performance

Date	Test Hours	E (volts)	R (ohms)	P (watts e)	P _T (watts t)	T _c (°F)	T _h (°F)
12-12-67	159	53.2	9.69	72.8	1104	191	1074
12-14-67	207.5	53.3	9.75	72.6	1108	193	1073
12-16-67	262	53.4	9.86	72.0	1112	194	1073
12-19-67	330	53.4	9.86	72.0	1112	193	1072
12-22-67	400	53.7	9.93	73.0	1116	194	1072
12-25-67	474	54.0	9.86	73.5	1124	190	1073
12-28-67	547	53.9	9.86	73.3	1124	192	1073

Key:

- E Instantaneous open circuit voltage
- R Internal resistance
- P Output power
- P_T Gross input power
- T_c Average cold electrode temperature
- T_h Average hot electrode temperature

Figure 3-8. SNAP-23A EMC No. 1 Performance During Stability Conditioning Period

The results of the tests run up to this point on EMC No. 1 indicate that the converter did not live up to design expectations electrically because of the excessively high P-leg resistance which lowered the output power significantly from the design value. Comparison of EMC No. 1 P-leg resistance ratios with those observed in the odd circuit of 10-couple module No. 1 (similar legs) and bell-jar tests 5 through 11 (converter legs) indicates very poor correlation of EMC No. 1 performance with data observed previously on the SNAP-23A Program (refer to appropriate sections of this report). Identification of the cause of this phenomenon is very difficult. However, current plans are to attempt to duplicate this phenomenon in a bell jar test.

From a thermal standpoint, EMC No. 1 performed as expected with one notable exception; namely, the temperature drop from the cold electrode to the outer case had a nominal design value of 30°F compared to observed values of 47 and 56°F at EOL and BOL design conditions respectively. This difference is probably the result of an unfavorable tolerance stack up between the spherical radii of the cold caps and followers causing a higher temperature drop across this interface. The gradual increase in input power required to maintain constant temperatures during the stability conditioning period is similar to the trend observed previously on 10-couple module No. 1, and is apparently caused by a thermal conductivity increase in the Min-K 1301 insulation as a result of gas buildup.

3.2.3.2 Individual Couple Analysis

The EMC No. 1 converter is instrumented at three horizontal row positions: the top, bottom, and middle. Temperatures, both hot and cold junction, and voltage are measured at these points. With this information, P- and N-leg performance can be separated, and differences due to location along the heat input stud can be noted. Overall leg resistance, R_T , is calculated using open circuit voltage, load voltage, and current. These parameters are related by the expression

$$V = E - IR_T$$

where

E = open circuit voltage

V = load voltage

FIXTURE LOSS

UPPER	LOWER
.79	1.45
2.26	3.10
1.86	4.35
.85	2.48
.43	1.80
.98	1.01
1.27	.78
8.44	1.10
	.90
	.71
	.52
	.15
	18.35

NET BOUNDARY TRANSFER

UPPER-OUT	IN	
2.85	1.05	
1.09	.75	
1.77	.25	
1.38	2.05	NET 5.04
7.09		
LOWER-OUT	IN	
0.75	1.39	
	1.39	
	2.78	NET 2.70

MISCELLANEOUS LOSS

EOL LOSS = BOL LOSS $\times \frac{EOL \Delta T}{BOL \Delta T}$
 $= 4.6 \times \frac{930 - 125^{\circ}F}{1125 - 132^{\circ}F} = 3.7 \text{ WATTS}$

POWER IN 864 WATTS

UPPER FIXTURE 8.44 WATTS
NET BOUNDARY +5.04 WATTS
LOWER FIXTURE 18.35 WATTS
NET BOUNDARY +2.70 WATTS
NET STATION 29.13 WATTS
MISCELLANEOUS 3.7 WATTS
TOTAL LOSS 32.83 WATTS
POWER OUT 50.9 WATTS
 $EFF = \frac{50.9}{864 - 32.8} = .0612 = 6.12\%$

KEY

- MEASURED TEMPS
- CALCULATED TEMPS
- HEAT FLOW (WATTS)

BLANK

Figure 3-10 Thermal Analysis SNAP-23A Converter Process and Test Station

BLANK

Solving for R_T

$$R_T = \frac{E - V}{I}$$

Leg material resistance, R_M , is calculated from a computer program which has the new recharacterization coefficients for simultaneously pressed legs. Extraneous electrical resistance, R_e , is equal to the difference between R_T and R_M or

$$R_e = R_T - R_M$$

In comparing data, extraneous resistance has been discussed as a percentage of total resistance in which case

$$\%R_e = \frac{R_e}{R_T} \times 100$$

This percentage for N-legs has shown a slight negative value in some instances. This, of course, is impossible and is probably due to inaccuracies in measuring instruments and recharacterization coefficients, plus leg geometry variations permitted by manufacturing tolerances on leg lengths, diameters, and segment concentricity. Resistance ratio, RR, is another method of comparing extraneous resistance and is denoted by the relation

$$RR = \frac{R_T}{R_M}$$

Seebeck or open circuit voltage, E , is compared by means of a ratio which is calculated by the expression

$$SR = \frac{E_{act}}{E_{theo}}$$

where

SR = Seebeck ratio

E_{act} = actual or measured Seebeck voltage

E_{theo} = calculated or theoretical Seebeck voltage based on measured temperatures

Actual power output is compared to theoretical power output using the ratio

$$PR = \frac{P_{act}}{P_{theo}}$$

where

$$P_{act} = \text{experimental matched power} = \frac{E_{act}^2}{4 R_T}$$

$$P_{theo} = \text{theoretical matched power} = \frac{E_{theo}^2}{4 R_M}$$

The theoretical power output is based on material resistance, R_M , which means that the extraneous electrical resistance is zero. This provides a common base for comparison and represents the maximum power a leg could achieve. This ratio should always be less than 1.00. As in the case of negative extraneous electrical resistance, a power ratio greater than 1.00 implies measuring inaccuracies and leg geometry variations. Based on the foregoing derivations, leg parameters are compared in Tables 3-9 and 3-10.

It is noted in the tabulation for EOL conditions that the average values for hot and cold junction temperatures are within one degree of the design temperatures, 900° and 174°. If the power ratio of 0.836 is applied to predicted design power of 60.24 watts, the actual power would be

$$P_{act} = 0.836 \times 60.24$$

$$P_{act} = 50.4 \text{ watts}$$

This corresponds very closely to EMC No. 1 measured power of 50.9 watts.

Table 3-9. SNAP-23A EMC No. 1 Thermoelectric Leg Parameters - BOL

Leg Location and Type	T _h	T _c	% R _e	RR	SR	PR
Top - P	1069	215	31.9	1.47	1.02	0.709
Top - N	1073	200	- 3.3	0.968	0.990	1.01
Top - P	1078	207	26.5	1.36	1.00	0.736
Top - N	1078	179	- 3.1	0.969	0.988	1.01
Middle - P	1086	184	32.2	1.47	1.01	0.698
Middle - N	1086	187	- 1.2	0.988	0.992	0.996
Bottom - P	1093	184	30.5	1.44	1.01	0.703
Bottom - N	1100	214	- 7.4	0.931	0.981	1.03
Averages	1083	196	13.3	1.200	0.999	0.861

Table 3-10. SNAP-23A EMC No. 1 Thermoelectric Leg Parameters - EOL

Leg Location and Type	T _h	T _c	% R _e	RR	SR	PR
Top - P	898	180	33.4	1.50	1.00	0.672
Top - N	898	162	- 0.645	0.994	0.992	0.990
Top - P	890	187	43.6	1.77	1.06	0.629
Top - N	889	180	0.90	1.01	1.01	1.01
Middle - P	907	165	43.4	1.77	1.07	0.651
Middle - N	907	169	0.157	1.00	0.994	0.986
Bottom - P	906	164	33.6	1.51	1.05	0.726
Bottom - N	910	190	- 3.54	0.965	0.994	1.02
Averages	901	175	18.9	1.315	1.021	0.836

3.3 PROTOTYPE MOCKUP CONVERTER

3.3.1 DESIGN

Major design efforts and decisions during this quarter for the Prototype Mockup Converter included:

- 3M and Westinghouse agreement to establish the Prototype Mockup Converter interface to be the same as those of the Experimental Mockup Converter in the following areas:

Physical interface dimensions

Same amount of internal instrumentation

Same instrumentation location where location effects component configuration

Preliminary hot and cold side thermal conditions

Electrical performance requirements

- Cold frame study
- Cold cap and follower socket design study
- Investigations in the areas of tolerance relaxation, heat transfer, extraneous resistance and performance (power output), and thermoelectric couple performance
- Determination and engineering release of part designs which have commonality between the Experimental Mockup and Prototype Mockup Converters

3.3.1.1 Cold Frame Tooling Study

Although the Experimental Mockup Converter cold frame is designed so it can accommodate up to 294 couples, manufacture of a cold frame which could accommodate more than 280 couples requires special tooling.¹

¹Due to improved vendor equipment, this is no longer the case.

Table 3-11. Heat Balance Tabulation

L_P	L_N	Extraneous Resistance	T_c EOL	T_h EOL	Rejected Heat, EOL	Rejected Heat EOL	Total Heat Input BOL (Ability to Absorb Heat)	F_{in} Rejection Rate EOL	F_{in} Rejection Rate BOL	Available Heat at BOL	Power Output EOL
0.326	0.463	6.33	170	862.6	725.8	924.9	1094.1	662.2	872.3	1004.9	86.2
0.302	0.429	13.3	170	862.6	784.1	999.5	1150.6	662.2	872.3	1079.5	86.1
0.322	0.453	6.33	180	867.6	731.4	931.9	1095.6	785.8	1004.2	1011.9	85.5
0.298	0.419	13.3	180	867.6	790.2	1007.1	1153.9	785.8	1004.2	1087.1	85.5
0.316	0.443	6.33	190	873.8	739.4	942.2	1100.5	912.9	1138.4	1022.2	85.0
0.293	0.410	13.3	190	873.8	798.9	1018.3	1158.1	912.9	1138.4	1098.3	85.0
0.311	0.432	6.33	200	879.6	747.0	952.0	1105.3	1044.2	1275.8	1032.0	84.5
0.288	0.400	13.3	200	879.6	807.1	1028.9	1163.9	1044.2	1275.8	1108.9	84.5
0.325	0.458	6.33	175	865	728	927.2	1093.0	728	927.2	1007.7	85.7
0.298	0.419	13.3	180	867.8	790.1	1007.3	1153.4	790.1	1007.3	1087.1	85.4

BOL Temperatures = $1085^\circ T_h$ and $T_c = T_{C_{EOL}} + 17$ degrees

EOL Power = 60 watts (24 volts at 2.5 amps)

BOL Voltage = 24 volts

The purpose of this study is to determine if this tooling should be available or if the confidence level in the present cold frame design (280-couple capacity) overrules this possibility for the PMC.

To avoid a lengthy parametric study involving the effects of several input variations as applied to various number of couples, the critical number of 280 was examined for heat compatability with the fin type rejection system at several cold junction temperatures.

The following curves and tabulation show that an optimized, 280-couple converter can develop 60 watts at EOL without exceeding the present heat rejection capacity of the fins. This also holds true for a 13.3% extraneous resistance converter which has a higher heat rejection rate for the same power output. Checking each design at BOL conditions showed each P-leg segment temperature to be under 600°F and the heat absorption capacity to be greater than the available heat.

In Figure 3-11, the 280-couple converter cold junction temperatures are plotted against heat rejected by the fins for an extraneous resistance of both 6.33% and 13.3%¹. Fin heat rejection capacity, corresponding to various cold junction temperatures, is also plotted so that the point at which converter heat rejection rate equals fin capacity can be determined. For 6.33% extraneous electrical resistance, the two curves intersect at a T_c of 175°F and a Q_R of 728 watts for EOL conditions. Since the converter was optimized for each cold junction temperature, the P- and N-leg geometry corresponding to 175°F can be determined from Figure 3-11. The corresponding hot junction temperature for each extraneous resistance is shown in Figure 3-12 and is 865°F for a converter having 6.33% extraneous resistance. Table 3-11 is a heat balance tabulation which also contains data pertaining to BOL conditions. The primary concern at BOL is that the converter can absorb the available heat without exceeding a hot junction temperature of 1085°F and that the fins have the capacity to absorb the converter rejection heat. For the balanced condition noted in Figure 3-11 where T_c equaled 175°F, the tabulation shows that at a T_h of 1085°F, the converter can absorb 1093 watts which is greater than the available heat of 1007.7 watts².

¹Extraneous resistance value experienced with SNAP-23 converters.

²BOL available heat is equal to EOL heat input to converter divided by decay factor.

Figure 3-11. Heat Rejection and Leg Geometry Characteristics for Optimized, 280-Couple, 60Watt Converter at EOL

Figure 3-12. Couple Cold Junction Temperature versus Hot Junction Temperature at EOL

It is noted in the tabulation that fin capacity increased with temperature such that if EOL conditions were satisfied, BOL fin capacity would be adequate. The temperature rise of 17°F between EOL and BOL cold junction temperatures increased fin capacity at a rate equal to change in converter heat rejection rate between BOL and BOL. Therefore, an abbreviated tabulation concerning only EOL conditions can be shown as follows.

<u>Cold Junction Temperature, °F</u>	<u>Extraneous Resistance,</u>	<u>Excess Fin Capacity, watts</u>
170	6.33	-63.6
170	13.30	-121.9
175	6.33	0
180	6.33	54.4
180	13.30	-4.4
180	13.30	0
190	6.33	173.5
190	13.30	114.0
200	6.33	297.2
200	13.30	237.1

At 170°F and 6.33% extraneous resistance, the tabulation shows the fins are incapable of absorbing the converter rejected heat (shunt heat loss plus thermopile heat) by an amount equal to 63.6 watts. However, at 175°F the fin absorption rate exactly equals the converter heat rejection rate. At 190°F the fins have far more capacity than is required leaving allowance for converter variations such as increased extraneous resistance, increased thermal conductivity of leg material, and increased shunt heat loss. Each variation will be discussed separately. Couple number predictions are based on one variation occurring at a time.

1. Converter Resistance

An increase in extraneous resistance and leg material resistance have the same effect on the converter. The tabulation shows that the large excess fin capacities at cold junction temperatures in excess of 190°F indicate that 280 couples will not be exceeded for reasons of increased resistance. The confidence level for this prediction, based on past material and extraneous resistance data is 100%.

2. Shunt Heat Loss

A considerable increase in shunt heat loss can be tolerated at cold junction temperatures in excess of 180°F for the 6.33% extraneous resistance. Therefore, the confidence level in not exceeding 280 couples, based on recent data for powdered Min-K thermal conductivity, is 100%.

3. Leg Material Thermal Conductivity

The large excess fin capacities at the higher cold junction temperatures indicate that a large change (approximately 50% since conducted heat is approximately 570 watts) in material thermal conductivity can be tolerated. The confidence level in not exceeding 280 couples is 100%.

4. Reduced Fin Performance

The excess fin capacity of 297 watts at the 200°F cold junction point represents approximately 29% of present fin capacity. Because of the difficulty in analyzing fin performance when air circulation through the fins is partially restricted by the enclosure, the confidence level in not exceeding 280 couples is 75%.

5. Reduced Seebeck Coefficient

A 5% reduction in Seebeck coefficient was considered which affects the reversible phenomena such as Peltier and Thompson heat values

in addition to the Seebeck voltage. An approximate calculation indicated no excess couple problem. However, in view of possible calculation errors, the confidence level in not exceeding 280 couples is 75%.

Considering the probability of the foregoing variations happening and the compensating possibilities if they should occur, it was recommended that no tooling be ordered for a 294-couple cold frame.

3.3.1.2 Cap and Follower Socket Design

The SNAP-21 Program (Contract AT(30-1)3691) conducted a study on cold cap and follower design as related to temperature gradient between cold cap and cold frame. Because of the similarity between the SNAP-21 cold cap and follower design to the same SNAP-23A parts design, it appeared that much of this test data would be applicable. Both designs used the ball and socket principle, the SNAP-21 design having a 0.125-inch spherical radius as compared to a 0.109-inch spherical radius for the SNAP-23A socket. The present SNAP-23A design consists of a nickel plated copper cold cap and a totally hard coated aluminum follower. Two high heat transfer barriers are encountered with totally hard coated followers: the coating in the socket seat which restricts heat flow between the cap and follower, and the coating on the follower shank which restricts heat flow from the follower to the cold frame. Since a high temperature drop between cold cap and cold frame reduces converter efficiency, the SNAP-23A Program is concerned with techniques for reducing this temperature drop without sacrificing electrical reliability¹ and long-term performance².

The SNAP-21 study covered variations on cap and follower design such as indium plated cold caps against hard coated follower sockets, indium plated cold caps against solid beryllium oxide followers, and bare copper cold caps against solid beryllium oxide followers. Sufficient data has been gathered to show a trend

¹Electrical short between cold cap and cold frame.

²The post-test analysis of the SNAP-23 converter showed that socket grease had disappeared.

between the various designs. However, additional data should be generated before conclusive design decisions can be reached. Tests for studying exact SNAP-23A geometry, using nickel plated cold caps and beryllium oxide followers, are planned. Results will apply to the Prototype Mockup Converter. The following discussion is a digest of the SNAP-21 study program.

Temperature gradients from cold cap to cold frame for several design variations are shown in Figure 3-13. Some of the variations are shown as a single point rather than a curve, each point being the average of several readings for parts where the spherical radius on cap and follower were very nearly equal. The number in parenthesis next to the point represents the number of points which were averaged. It is noted in Figure 3-13 that a low temperature drop is achieved with the non-hard coated (NHC) design as compared to the hard coated (HC) design. The concept of a non-hard coated follower socket, however, removes a redundant electrical barrier, and therefore it was advisable to subject the hardware to vibration.

A two-couple module was modified to facilitate vibration testing of four assemblies of the NHC type. Converter temperature conditions were simulated and the module was vibrated between 5 and 250 Hz. The most severe test was at the 10 g level where the frequency range was swept at a rate of one octave per minute in the axial and transverse axes of the body. In the transverse axis a form of resonance was noticed at 160 Hz in the 3 g, 6 g, and again in the 10 g test. After the frequency sweep, the resonant point was found and held for 15 minutes. No breakdown in the single electrical barrier (between follower shank and cold frame) was noted at any time during testing. Upon disassembly, the followers showed no wear or any change in appearance.

It is also noted in Figure 3-13 that a slightly lower temperature drop occurs when the follower socket radius is smaller than the cold cap radius thereby creating ring contact. The curves also show that extremely close tolerances on the radii are not necessary. From this information, the nominal cold cap radius could be 0.001 inch larger than the socket radius, each radius having a ± 0.001 tolerance.

Figure 3-13. Comparative Results of Heat Transfer Testing

Beryllium oxide followers are attractive from both the heat transfer and electrical resistivity standpoints. At a temperature of 200°F, BeO thermal conductivity is equivalent to that of aluminum. Also, the possibility of an electrical short between cold cap and cold frame is eliminated because of the inherent high electrical resistivity of BeO.

Typical test results are shown in Table 3-12. It is interesting to note that spring pressure had very little effect on temperature drop as recorded in tests 1 and 2. Radial dimensional difference between socket and ball, the interjection of a soft foil between ball and socket, and a hard or non-hard coated socket seat all show a considerable temperature drop change. Test results for EMC No. 1 are shown in Table 3-13. Thermocouples were located at the top, bottom, and middle of the device. In comparing Table 3-13 data to Table 3-12 data for hard coated followers, a close correlation is noted.

Referring to Table 3-12, $T_c - T_{cf}$ is considerably higher when the follower is substantially greater (0.004 inch) than cold cap ball radius. Tolerances on the EMC No. 1 parts permitted the socket radius to vary from 0 to 0.0015 inch larger

Table 3-12. SNAP-21 Heat Transfer Development Tests

Socket Seat	Cold Enc Hardware	Spring Pressure, psi	Follower Seat Radius	Cold Cap Ball Radius	Cold Cap Temp, T _c , F	T _c -T _{cf}	T _f -T _{cf}
HC	SNAP-27 Precision	150	0.12535	0.1250	120.5	46.5	18.0
HC	Phase I Residual	150	0.1273	0.1235	143.5	69.5	14.5
HC	SNAP-27 Precision	150	0.1250	0.1250	119.5	45.5	13.5
HC	Phase I Residual	150	0.1275	0.1235	138.5	64.5	17.0
HC	SNAP-27 Precision	250	0.12535	0.1250	119.5	44.0	11.5
HC	Phase I Residual	250	0.1273	0.1235	154.5	79.0	9.5
HC	SNAP-27 Precision	250	0.12535	0.1250	121.0	45.5	9.5
HC	Phase I Residual	250	0.1275	0.1235	139.5	64.0	9.5
HC	SNAP-27 Precision	150	0.12535	0.1250	118.5	44.5	8.0
NHC	SNAP-27 Precision	150	0.1250	0.1250	95.0	21.0	8.0
HC	SNAP-27 Precision	150	0.12535	0.1250	121.0	47.0	7.0
NHC	SNAP-27 Precision	150	0.1250	0.1250	88.0	14.0	9.0
HC	SNAP-27 Precision	150	0.1253	0.1250	102.0	28.5	5.5
with 0.001 Lead Foil in Gap	Phase I Residual	150	0.1274	0.1235	122.0	48.5	4.0
	SNAP-27 Precision	150	0.12535	0.1250	101.5	28.0	7.0
	Phase I Residual	150	0.1275	0.1235	105.5	32.0	7.5
HC	SNAP-27 Precision	150	0.12535	0.1250	127.0	43.0	7.5
with 0.001 Gold Foil in Gap	Phase I Residual	150	0.1274	0.1235	137.5	53.5	10.0
	SNAP-27 Precision	150	0.12535	0.1250	123.0	39.0	9.0
	Phase I Residual	150	0.1275	0.1235	125.0	41.0	7.0
Unless otherwise specified:		Average T _h = 1100°F		Internal gas pressure = 3 psig			
		Average T _{cf} = 75°F		HC = hard coated			
				NHC = non-hard coated			

Table 3-13. SNAP-23A EMC No. 1 Test Data

Device Location	T_h , °F Average	T_c , °F Average	$T_c - T_{cf}$ °F	$T_c - T_{oc}$ °F
Top	BOL or	BOL or	47	64
Middle	1085	191	42	49
Bottom			58	60
Top	EOL or	EOL or	38	53
Middle	900	174	37	43
Bottom			46	48

Cold Cap – Nickel plated copper

Follower – Hard coated aluminum (entire surface)

Cold cap ball radius – 0.1085 ± 0.0005

Follower socket radius – 0.10925 ± 0.00025

Back fill gas – Argon

Internal gas pressure – 10 psig

Spring pressure – 250 psi

than the ball radius. Although there is a difference in cold junction temperatures between EMC No. 1 and the devices tested in Table 1, there is a reasonable correlation between temperature gradients for devices with design similarities. Because of a very high temperature gradient with xenon gas (101°F at BOL conditions), the EMC No. 1 converter was flushed and refilled with argon gas. Average converter temperature gradient ($T_c - T_{oc}$) with argon at BOL conditions dropped to 68.7°F.

3.3.1.3 Tolerance Relaxation

Unnecessarily close tolerances add considerable cost to converter components, especially where fabrication of a component involves extensive machining. One specific area which involves many critical tolerances is the system for maintaining true alignment of the thermoelectric legs. No conclusive evidence is available from prior work on whether misalignment is detrimental to performance. As reported in paragraph 4.4.2 of this report, several bell jar tests (Nos. 8/18-10,

9/18-12 and 11-14) were initiated this quarter to provide leg misalignment data.¹ Results of the misalignment versus performance relationship established from these tests will be factored into the Prototype Mockup Converter design.

3.3.1.4 Insulation Thermal Conductivities

Design conditions for insulation thermal conductivities were formulated and are listed below. Recommended thermal conductivity values for these design conditions have been established as discussed in paragraph 3.2.2.2 and will be utilized in the PMC design.

1. Gas	Argon or xenon
2. Insulation	Processed powdered Min-K 1301 Processed molded Min-K 1301 Microquartz
3. Absolute internal converter pressure prior to outgassing	25 psia
4. Temperature range	140° to 1100°F
5. Leak rate (maximum allowable)	1×10^{-6} cc of He per sec at standard conditions
6. Density of powdered Min-K 1301	12.5 lbs/cu. ft.
7. Density of Microquartz and molded Min-K 1301	Johns-Manville book values
8. Thermal conductivity values	Maximum value at EOL and value at time of delivery

3.3.1.5 Extraneous Resistance and Performance (Power Output)

Data was studied this quarter relating the effect of increased contact resistance at the hot junction electrode on performance. Accurate effects of misalignment

¹The post-test analysis of the SNAP-23 converter indicated up to 6 degrees of tilt for the lower couples.

on contact resistance are difficult to determine because the results are affected by possible migration of the following:

- (1) powdered insulation between the hot end of the leg and hot junction button
- (2) the compensating effect of material creep during "seating-in", and
- (3) the inability to differentiate between experimental and theoretical leg material resistance.

Since net "contact" resistance cannot be isolated from total extraneous resistance in practical devices (which includes the resistance of the cold junction electrode, hot junction electrode, hot junction buttons, contact resistance, and power leads), the data studied considered total extraneous resistance rather than only "contact" resistance.

A summary of comparative data for performance versus extraneous resistance is given in Table 3-14. Design decisions based on this data will be made when further data is accumulated from the SNAP-23A 10-couple module and bell jar tests, and from the investigation of application of results from the SNAP-23A material characterization effort (see Section 4.2.2). In Table 3-14, extraneous resistance is shown as a percent of total device resistance, determined by the difference between measured total resistance and theoretical resistance (computer-predicted). As such, a negative value for extraneous resistance implies that the measured value is less than the predicted value.

3.3.1.6 Couple Performance

Couple performance data as related to the following conditions for the SNAP-23, SNAP-23A, SNAP-21, and SNAP-27 programs was examined.

1. Fabrication method (simultaneously pressed with conventional and soft nose; separately pressed and bonded with conventional and soft nose)
2. Follower spring pressure

Table 3-14. Thermoelectric Converter Performance Comparison

Unit	Percent Over or Under Theoretical Power	Extraneous Resistance in Percent of Total Resistance	*Leg Fabrication Technique
SNAP-23 Converter	+5.6	+8.5	SP, N
SNAP-21 P-6 Converter	-15.2	+23.8	SP, N
SNAP-21 10D2 Converter	+5.8	+1.8	B, H
SNAP-27 Module #10	-6.0	+6.0	Non-segmented Conventional
SNAP-27 Module #15	-9.7	+9.3	Non-segmented Conventional
SNAP-23A 10-Couple Module	-4.3	+8.2	SP, N
SNAP-23A 10-Couple Module	-8.3	+9.3	SP, H
SNAP-23A 10-Couple Module	+16.5	-19.4	B, N
SNAP-23A 10-Couple Module	+11.0	-14.4	B, H
SNAP-23A Bell Jar	-1.2	+0.93	SP, N
SNAP-23A Bell Jar	-5.0	+0.45	SP, H
SNAP-23A Bell Jar	+16.5	-26.6	B, N
SNAP-23A Bell Jar	+11.3	-17.3	B, H

*SP: Simultaneously Pressed Segments

B: Individually Pressed and Bonded Segments

N: Conventional

H: Soft Nose

3. Seating-in temperatures
4. Operating temperatures
5. Misalignment
6. Gas
7. Gas pressures

The Prototype Mockup Converter leg fabrication method will not be selected until actual designs have been compared, using the new material coefficients and extraneous resistances as determined from 10-couple module and bell jar tests.

3.3.2 FABRICATION AND ASSEMBLY

The major components listed below were at various stages of completion and on a hold at the end of the reporting period; pending resolution of the overall integrated Prototype Mockup Converter and system schedule and design considerations

1. Upper Support Cone
2. Outer Case
3. Lower Cover
4. Cold Frame
5. Hot Frame
6. Heat Source Simulator

The insulation strips, followers, and thermoelectric couple hardware designs have not been released. Minor components have not been released except for the headers, which are long lead items.

3.4 SUPPORT EQUIPMENT

3.4.1 PROCESS AND TEST STATION

3.4.1.1 Design

Design of the Process and Test Station was essentially completed during the last quarter. Efforts this quarter consisted primarily of engineering follow-up on problems related to the Process and Test Station design identified during assembly and processing, and resulted in the following actions:

1. In the assembly of two readout panels, chromel-alumel pin receptacles were used in place of iron-constantan. The wrong receptacles were delivered by the vendor. Correction by the vendor required a lead time unacceptable to program needs. As a result, a design investigation was conducted, and a decision was made to use the chromel-alumel pin receptacles.
2. Water lines were rerouted away from the critical power supply and from instrumentation read-out equipment inside of the Process and Test Station; plastic tubing was replaced with metallic tubing in the critical areas.

3.4.1.2 Fabrication and Assembly

During this quarter, fabrication of Process and Test Station Console No. 1 was completed, and the station was used during Experimental Mockup Converter No. 1 processing. Fabrication of Console No. 2 (to be used for EMC No. 2 processing) was completed, and Consoles 3 and 4 were partially assembled. The outstanding items for both Consoles 3 and 4 are the 39-TL-1009 Panel and the cabinet to house the various components.

The major problems encountered in test station console fabrication were the difficulty experienced in filling the Chromel-alumel and Iron-Constantan solder cups on the connectors prior to installing the wires, and the difficulty of soldering the solid Chromel-alumel thermocouple wires and the Iron-Constantan thermocouple wires to their connectors and terminals.

The following processes were developed and used successfully to solve the soldering problems.

1. Filling solder cups of connectors
 - a. Insert one drop of Ersin liquid flux, formula #5380 into cup.
 - b. Heat cup with resistance soldering iron (Wasco #105105) set at 70-80 watts.
 - c. Apply 60-40 (Kester #44) rosin core solder.
2. Preparation of wires
 - a. Clean wires with alcohol.
 - b. Tin wire using 60-40 (Kester #44) rosin core solder).
 - c. Clean tinned wires with alcohol.
 - d. Reheat cup and insert wire.

3.4.2 SHOCK AND VIBRATION FIXTURE

During this quarter the design for the shock and vibration fixture was released and the fixture fabricated.

3.4.3 SHIPPING CONTAINER

During the quarter the shipping container (Figure 3-14) was designed and a plan drawn up for handling the packaged converter during transport.

The converter is supported by standoff bolts inside of a heavy gauge sheet metal drum. A tubulation fitting (not shown) is located in the drum cover for replacing the confined air with an inert gas such as argon during shipping preparation. A three axis accelerometer is installed in the drum.

SPECIFICATION

STYLE

CLEATED PLYWOOD BOX
CONSTRUCTED TO CLIMCO
SPECIFICATIONS

DIMENSIONS (INSIDE)

L - 31-7/8 W - 31-7/8 D - 39

MATERIAL

PLYWOOD 3/8 THICK
GRADE, EXTERIOR A/C
CLEATES NOMINAL 1 THICK
GRADE, CLEAR PINE
SKIDS NOMINAL 1 X 4

HANDLES

4 EA TOTAL 2 EA, 2 SIDES
CHEST TYPE (90° STOP)

Figure 3-14. SNAP-23A Converter Shipping Container

After sealing off the drum it will be placed in the plywood container. The drum will be supported by both rigid and flexible foam as shown in Figure 3-15.

The handling plan worked out with Northwest Airlines calls for 3M personnel to accompany the converter. Airline personnel will be informed of the nature of the shipment and will be directed to assist 3M personnel to carry the packaged converter to the aircraft side where it would be loaded before other baggage. At the destination, clearance would have been arranged for 3M to monitor unloading the converter from the aircraft. In case of inclement weather and a change of landing destination, the new destination would be altered and similar unloading arrangements made.

Figure 3-15. Concept for SNAP-23A Converter in Shipping Container

3.5 QUALITY ASSURANCE

3.5.1 QUALITY CONTROL

Experimental Mockup Converter No. 1 was quality monitored through assembly processing during this quarter.

A joint functional review of the Manufacturing Flow Plans and routing sheets was held at the completion of processing operations to assure that any departures or changes were properly documented and adequately dispositioned prior to releasing the converter to test for initial performance verification testing and stability conditioning.

The review and release steps (Toll Gates) incorporated on the Manufacturing Flow Plans and Process Routing Sheets are to be completed prior to starting the next operation. These steps have been added prior to shrink fit, welding, processing, and acceptance testing.

An additional preventive measure, the polarity check, was devised for use on the converter thermopile to detect potential reverse orientation of the thermocouples in the assembly.

During assembly of the Experimental Mockup Converter No. 2 thermopile, a photographic record was made of each row of couples as it was being installed into the thermopile to show proper N-leg and P-leg orientation (Figure 3-16).

A weld schedule was developed for Experimental Mockup Converters from weld samples simulating converter edge and output header weld configurations. The procedures and settings used to prepare the samples were documented and the edge weld samples were X-rayed and submitted, along with the headers, for metallurgical examination. However, a burn back approximately 3/4 inches long was experienced on EMC No. 1 hot frame/lower cover edge weld. Investigation revealed the converter was welded in accordance with the schedule established from the samples, but the heat sink area of the sample was greater than that of the converter.

Figure 3-16. Individual Row Thermocouple Orientation
Photographic Record

A revised weld schedule was prepared for use on EMC Nos. 2 and 3. In revising the weld schedule, the following steps were taken. New weld samples were machined in accordance with Figure 3-17 simulating the lower cover and hot frame joint; Figure 3-18 simulating the lower cover and outer case joint; and Figure 3-19 simulating the support cone and outer case. Figure 3-20 is a sketch showing the corresponding converter weld areas represented by the samples. The samples were welded with 100 percent surveillance by Quality Control documenting the process used for each weld.

X-rays of the welded samples were taken for determination of porosity and penetration indicating the samples were within the requirements specified in the welding specification.

Further evaluation of the weld samples were made by metallographic examination. The samples were sectioned, polished and etched, and indicated acceptable welds (Figure 3-21).

Figure 3-17. Lower Cover/Hot Frame EMC No. 2 Weld Sample

Figure 3-18. EMC No. 2 Lower Cover/Outer Case Weld Sample

Figure 3-19. EMC No. 2 Support Cone/Outer Case Weld Sample

Figure 3-20. Sketch Showing SNAP-23A Converter Weld Areas

a Lower Cover/Hot Frame

b Support Cone/Outer Case

Figure 3-21 Typical Experimental Mockup Converter No. 1 Revised Weld Schedule Samples

All deviated interface dimensions requiring Westinghouse concurrence were transmitted to Westinghouse and concurrence was received.

The Manufacturing Flow Plans and Process Routings used for the build of EMC No. 2 were updated, incorporating the experience gained from EMC No. 1.

The following QA standards were prepared and implemented during this quarter:

QA-STD-54 Total Resistance Measurement

QA-STD-28 Inspection

QA-STD-59 Thermoelectric Powder Inspection

QA-STD-33 Material Review Procedure was revised and the SNAP-23A Quality Control Program Plan has been updated to include this revision.

Lists were revised to include interface dimensions for assembly drawings.

3.5.2 RELIABILITY

The majority of reliability effort conducted during the reporting period was devoted to monitoring the assembly of Experimental Mockup Converters, Nos. 1 and 2. The objective of this monitoring effort was to observe all operations in the assembly process procedures which may result in either short or long term performance degradation of the converter. Also, many of the assembly steps rely on the use of a high skill level under the cognizance of experienced supervisors. These steps were monitored to assure that the full intent of the procedure was not compromised by erroneous performance of the detailed steps.

A number of reliability investigations were carried out on components and processes used in the converter assembly. These investigations included:

1. The effects of acid fluxes and their removal processes on the hermetic headers and the connector assemblies; this investigation was carried out by applying the fluxes and solvents to representative parts in a number of sequences and combinations which would represent worst case manufacturing conditions. The effects were measured with an ohmmeter and

a 500 vdc megohmmeter. These tests showed that the acid fluxes do not have a detrimental effect on either the header or the connector if they are properly cleaned.

2. The reliability of the solder bond between the cold caps and the jumper wire: this was reviewed to determine the effect of design changes (see Quarterly Report No. 2, paragraph 4.5.3, for original investigation). A number of production samples were examined visually and given pull tests on the solder bond. All of the samples tested far exceeded the strength requirements of the part, but a 100 percent pull test was added to the soldering process to assure the integrity of all bonds.
3. The primary reason for malfunctioning of Experimental Mockup Converter No. 1 transducer: it was concluded from the investigation that the transducer malfunction was not the result of errors in converter associated circuits but was the result of improper handling, subjection of the transducer to too hard a vacuum during processing, and excitation of the transducer during processing. As indicated previously in paragraph 3.2.2 of this report, although the vendor was aware of our usage, no precautionary handling or environmental limitation information was supplied by them until additional inquiries were made after the unit failed. Corrective action was recommended and has been included for Experimental Mockup Converter No. 2 as described in paragraph 3.2.1.1.
4. An investigation was conducted to determine if discolored spots (approximately 1/8 inch in diameter) on the follower barrel would effect dielectric strength of the material. No tendency of the discolored areas to short was observed.

SECTION 4.0
TASK III – THERMOELECTRIC COUPLE DEVELOPMENT

SECTION 4.0

TASK III-THERMOELECTRIC COUPLE DEVELOPMENT

4.1 INTRODUCTION

The major objective of the thermoelectric couple development program is to identify and provide solutions for problem areas related to 10-year life thermoelectric leg stability. This effort is being conducted concurrently with the baseline converter development program primarily through the post-test analysis, bell jar testing, 10-couple module tests and SNAP-23 continuation testing. Test data from the various phases of the program are presented in paragraph 4.4. Phases of the program concerned primarily with design and fabrication of test units and thermoelectric leg development are presented in paragraphs 4.2, 4.3, and 4.5.

4.2 DESIGN

4.2.1 LEG AND COUPLE DEVELOPMENT

The design effort for the thermoelectric couples (Figure 4-1) used in the converters and 10-couple modules during this quarter was limited to engineering follow-up and corrective action during the manufacturing cycle. The following actions resulted from these follow-up investigations.

- a. Revised cold cap dimensioning method to aid inspection and manufacturing.
- b. Revised cold junction electrode. Wire size was changed from 16- to 20-gage to improve flexibility. The change in wire size is effective for all converters.

Figure 4-1. Thermoelectric Couple Sketch

- c. A 16-gage leg output wire was spliced just ahead of the header to provide a better output header pin fit (allowing only 0.001 to 0.002 inch clearance on a side).
- d. New acceptance criteria was established for the thermoelectric leg bond; a P-leg resistance requirement of not greater than 4.6 milliohms and a N-leg resistance of not greater than 3.4 milliohms was specified. In addition, visual requirements for absence of cracks, carbon chunks and foreign particles was reworded and a 5 percent maximum end chip requirement added. A solder material restriction on the leg cap spherical surface was added.
- e. The concentricity of the leg cold caps with the legs and the cold cap shoulder with the legs was re-evaluated and enlarged.

4.2.2 MATERIAL CHARACTERIZATION

As reported in Quarterly Report No. 3, the primary objective of this material characterization effort is to obtain data on thermoelectric leg properties which can be factored into and upgrade the current design data base for the SNAP-23A converters.

The thermoelectric properties of practical importance are the Seebeck coefficient S , the electrical resistivity ρ , and the thermal conductivity K , all of which are functions of the temperature. A thermoelectric leg operating in a temperature

gradient will exhibit a Seebeck voltage E relative to a given reference material (i. e., iron), a resistance R , and conduct heat at the rate of Q watts. The values observed depend upon the thermoelectric properties of the material and the junction temperatures. From a number of such observations made at a series of junction temperatures it is possible to determine values for S , ρ , and K as point functions of temperature.

The SNAP-23A baseline thermoelectric materials were characterized with the use of TELPS* equipment and procedures as indicated in Quarterly Report No. 3 (MMM 3824-0013).

4.2 2.1 General Description of TELPS Apparatus and Procedures

New apparatus, test procedures, and numerical data reduction techniques, which were developed under the TELPS program, permit determination of values of the Seebeck coefficient, thermal conductivity, and resistivity of an individual test specimen as a function of temperature over the temperature range of room temperature to 1300°F. The method is a transient ingradient performance test in which a test leg is subjected to a series of ever increasing temperature gradients each of which are measured for the hot and cold junction temperatures, Seebeck voltage, ingradient resistance, and conducted heat. The test fixture consists of TELPS ingradient performance test fixtures (Figures 4-2, 4-3, and 4-4) modified to include a thermal heat flux meter (Figure 4-5).

The ingradient performance fixture is essentially a four probe (two current and two potential) resistivity measuring device of special design to permit measurements to be made under one dimensional temperature gradient condition. Two Inconel sheathed iron-constantan thermocouples are compressively loaded against opposite ends of the test specimen along its central axis. The iron wires of each thermocouple are used as potential probes. Flat graphite current electrodes

*TELPS stands for Thermoelectric Leg Product Specification. This effort was conducted under SNAP-27, Contract AT(30-1)-3535.

Figure 4-2. TELPS Laboratory

Figure 4-3. Isothermal Furnace Used for Thermocouple Calibration

Figure 4-4. Ingradient Performance Fixture

Figure 4-5. Assembly of Thermal Conductivity Insert

are provided with an axial hole 0.090 inch in diameter through which 0.065 inch diameter thermocouples pass without touching. Insulating sleeves help ensure that the thermocouples (and thus, the potential probes) do not short out against the current electrode.

The current electrodes are attached to the thermoelectric legs in such a way that the current flows axially and radially in the cylindrical element, but no angular current flow exists. By defining the voltage distribution within the leg for a particular electrode and leg configuration, it is possible to devise a correction factor for the measured resistance. A resistance calculation based on the usual relation

$$R = \frac{(E - V)}{I}$$

would be in error because of non-uniform potential distribution near the electrodes. If we assume perfect contact between the electrode and the element, the voltage distribution within the element may be calculated.

The element is assumed to consist of uniform toroidal segments. Under steady current flow in the element, the net amount of electrical current flowing into each toroidal element must be zero. Therefore, we may write a current balance for each segment of the element.

Equations may be written for each segment of the element including the boundaries. A series of simultaneous equations is obtained which may be solved by relaxation procedures or matrix inversion.

An alternate method of determining the voltage distribution in the element is to assume a voltage distribution at some initial time and then calculate the voltage change for each segment as a function of time using finite difference techniques. This calculation is performed for each segment until a steady state is reached.

This second method was used in calculating the voltage distribution for the thermoelectric elements. The equations are analogous to the equations for heat transfer in cylinders. Therefore, a computer program which had been used for the calculation of heat transfer in cylinders was used for these calculations.

In the actual calculations, the use of a calculation method for non-steady state would require a very long time to reach steady-state conditions. However, it has been found in previous work that, for systems which are approaching steady state, when $\Delta E/\Delta t$ is plotted versus E and then extrapolated to $\Delta E/\Delta t = 0$, a good estimate of the steady-state value of E is obtained. With a computer, it is relatively easy to store values of $\Delta E/\Delta t$ and E at selected times and perform the linear extrapolation mathematically. After the extrapolation, the finite difference calculation may be continued for several more time increments to confirm that steady-state conditions have been determined. When the finite difference method, i. e., non-steady state technique, is used in conjunction with the extrapolation technique, the computer time required to calculate steady-state voltages is of the same order of magnitude as the time required for matrix inversion or relaxation methods.

The resistance correction factor was derived by obtaining an accurate potential map for an assumed potential difference of 1 volt. By finding the ratio of the measured voltage gradient $\frac{(E-V)}{L}$ to the average gradient near the center of the test specimen, we obtain the factor by which the measured voltage gradient gives too low an indication of the average voltage gradient in a region of the specimen where the current density is uniform. The resistance correction factor is then given by the ratio of the average gradient to the apparent gradient. It was found that the magnitude of this correction factor was not very sensitive to changes in leg diameter or small changes in length.

The ingradient performance fixture design provides a thermal environment which favors one dimensional heat flow in the test specimen as a consequence of the large temperature gradient and the large area isothermal hot block and cold block surfaces which tend to reduce lateral radiation heat loss. In addition, gas convection heat losses, as well as radiation loss through the quartz tube (which could produce sufficient change in the thermal gradient to cause a detectable change in resistance from that observed) are effectively eliminated by insertion of microquartz insulation into the vacant region surrounding the legs between the heater blocks.

4. 2. 2. 2 Thermocouple Calibration

The Inconel sheathed iron-constantan hot and cold junction thermocouples of the TELPS fixtures were calibrated against a calibrated standard thermocouple (Figure 4-6) which, in turn, had been calibrated against a Bureau of Standards secondary standard.

All the thermocouples were fabricated from wires of the same spools and were found to be in close agreement with each other, but they averaged about 8-10°F too high an indicated temperature in the 1300°F range compared to tabulated values. Thus, to convert thermocouple readings in millivolts to accurate temperature readings in degrees Fahrenheit, a two-step procedure was adopted. First, a 5th order least squares polynomial curve fit expressing temperature as a function of millivolt readings (referring to 32°F) was established and the six coefficients of the power series were stored in the appropriate data reduction programs.

A second order polynomial correction curve was then derived to express the average temperature error curve versus millivolt output. The calculated error for a given millivolt reading was then algebraically added to handbook temperature values to give corrected values. Since all thermocouples were referenced to a 150°F controlled reference junction terminal box, it was necessary first to add 1.22 mv to all thermocouple readings for correction to a 32°F reference junction temperature prior to entering the curve fits. The temperature was then calculated by:

$$T = A_0 + A_1 (mv)_1 + A_2 (mv)^2 + A_5 (mv)^5$$

It is estimated that this procedure gives temperature values accurate to within ±2°F or about 0.15 percent whereas, manufacturing J standards specify 3/4 percent accuracy.

Figure 4-6. Standard Thermocouple

4.2.2.3 Thermoelectric Material Characteristics

Test measurements were made on 3 to 6 samples of each of 5 types of materials. Four types of materials samples for simultaneously pressed segmented legs were obtained as separate segments from the same batches, and received the same manufacturing processing (i. e. , sintering) as those legs used in the first Experimental Mockup Converter. In addition, the fifth type of material tested is for the hot segment of separately pressed and bonded P-legs which have been undergoing test in bell jars and 10-couple modules.

The test data was analyzed with the aid of a digital computer to determine the material properties (S, K, ρ K) as functions of temperature in fifth-order polynomial form, e. g. ,

$$S (\mu V/^{\circ}K) = S_0 + S_1T + S_2T^2 + S_3T^3 + S_4T^4 + S_5T^5$$

$$K (\text{watts/cm-}^{\circ}K) = K_0 + K_1T + K_2T^2 + K_3T^3 + K_4T^4 + K_5T^5$$

$$\rho K (\mu \Omega \text{ watts}/^{\circ}K) = (\rho K)_0 + (\rho K)_1T + (\rho K)_2T^2 + (\rho K)_3T^3 + (\rho K)_4T^4 + (\rho K)_5T^5$$

The material coefficients in this form are used in several digital computer programs employed in the SNAP-23A Program, such as the program described in Quarterly Report No. 1 (MMM 3824-0006). Figures 4-7 through 4-22 are graphs of the material properties S, K, ρ as well as dimensionless figure of merit ($ZT = TS^2/K\rho$) versus temperature for the four materials of simultaneously pressed segmented legs for both SNAP-23 coefficients (dashed line) and the new SNAP-23A coefficients (solid line). Figures 4-23 through 4-26 are similar graphs for the hot segment material of separately pressed and bonded P-legs.

Validation of these material coefficients in computer programs for leg and couple design and parametric studies has been conducted by analysis involving the comparison of theoretical values with experimental data obtained from 10-couple module and bell jar tests, from large-scale thermopiles such as the 264-couple Experimental Mockup Converter No. 1, and from several SNAP-21 48-couple generators (particularly from the data for separately pressed and bonded legs).

Figure 4-7. Seebeck Coefficient (S)
(N Leg, Hot Segment
LTN-120, PbTe)

Figure 4-8. Resistivity (ρ)
(N Leg, Hot Segment
LTN-120, PbTe)

Figure 4-9. Thermal Conductivity (K)
(N Leg, Hot Segment
LTN-120, PbTe)

Figure 4-10. Dimensionless Figure of Merit (ZT)
(N Leg, Hot Segment
LTN-120, PbTe)

Figure 4-11. Seebeck Coefficient (S)
(N Leg, Cold Segment
LTN-400, PbTe)

Figure 4-12. Resistivity (ρ)
(N Leg, Cold Segment
LTN-400, PbTe)

Figure 4-13. Thermal Conductivity (K)
(N Leg, Cold Segment
LTN-400, PbTe)

Figure 4-14. Dimensionless Figure of Merit (ZT)
(N Leg, Cold Segment
LTN-400, PbTe)

Figure 4-15. Seebeck Coefficient (S)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure 4-16. Resistivity (ρ)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure 4-17. Thermal Conductivity (K)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure 4-18. Dimensionless Figure of Merit (ZT)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure 4-19. Seebeck Coefficient (S)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure 4-20. Resistivity (ρ)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure 4-21. Thermal Conductivity (K)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure 4-22. Dimensionless Figure of Merit (ZT)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure 4-23. Seebeck Coefficient (S) (P-Leg Hot Segment For Separately Pressed and Bonded PbSnTe)

Figure 4-24. Resistivity (ρ) (P-Leg, Hot Segment For Separately Pressed and Bonded PbSnTe)

Figure 4-25. Thermal Conductivity (K) (P-Leg, Hot Segment For Separately Pressed & Bonded PbSnTe)

Figure 4-26. Dimensionless Figure of Merit (Z T) (P-Leg, Hot Segment Pressed and Bonded PbSnTe)

The best measure or criterion for validation of these coefficients is seen in the comparison of experimental Seebeck voltage with computer-calculated (theoretical) Seebeck voltage for a given temperature gradient. As an example, these Seebeck ratios as shown in Table 4-1 for bell jar test data (Section 4.4.2) illustrate very close agreement of experimental versus theoretical values (in most cases, only 1 or 2 percent difference). A secondary "measure" is seen in the Resistance ratios determined similarly. However, the theoretical resistance calculated does not include any allowance for extraneous resistance such as couple electrode resistance and contact resistance. Therefore, this measure for validation of material characterization coefficients will have larger variations than the Seebeck criterion; but with good Seebeck correlation, it can be used effectively to determine extraneous resistance data for design purposes and analysis of test data generated for larger-scale devices.

4.2.3 10-COUPLE MODULE

The design effort for the 10-couple module was largely completed during the third quarter, and effort during this quarter was limited to engineering follow-up and corrective action during the manufacturing cycle. The following actions resulted from the follow-up investigations during the building of modules 5 through 12.

4.2.3.1 Modules 6 through 8

Problems encountered in attaching thermocouple wires to molybdenum hot buttons required a change in the method of instrumenting hot junctions; as a solution the diagnostic thermocouple was relocated from the hot button to the face of the electrode.

This solution was demonstrated to be satisfactory in exploratory tests; but during final assembly operations (insulation packing) on Modules 6-8, some of the thermocouple wires became detached. The following procedure was worked out to complete the assembly of those modules and still provide the minimum required voltage taps.

- a. All broken lead wires were removed from the thermopile to prevent possible short circuiting.
- b. Where constantan lead wires were broken no further action was taken; the loss of temperature data is recognized as a minor short-term consideration and is covered by redundancy on other electrodes.
- c. Broken iron wires were jumpered to the corresponding constantan lead. This allows voltage to be taken by correcting for the emf effect of the constantan voltage probe.

4.2.3.2 Modules 9 Through 12

As a result of the problems encountered in modules 6 through 8 the method of instrumenting hot junction was changed to mechanical attachment.

4.3 FABRICATION AND ASSEMBLY

4.3.1 THERMOELECTRIC COUPLE AND ASSOCIATED HARDWARE

Thermoelectric couples consisting of both simultaneously powder pressed N- and P-legs were fabricated for Experimental Mockup Converter EMC No. 1 during October 1967. These couples were first fabricated using a 16-gage copper jumper wire with a center-to-center electrode distance of 0.293. During final assembly of EMC No. 1, it was determined that the wire was too rigid for proper flexibility to reliably seat the thermoelectric legs into the hot buttons and to keep the cold end caps positioned into the cold follower spherical seats during temperature cycling of the converter.

The corrective action taken was to redesign and fabricate couples with a longer 20-gage wire having a 0.482 electrode center-to-center distance. The combination of a longer wire and smaller diameter provides the required degree of flexibility for all credible conditions with little sacrifice in lead power loss. The thermoelectric couples originally fabricated for EMC No. 1 were returned to bonded stock for further disposition.

Thermoelectric couples for EMC No. 2 were fabricated during November 1967. Thermoelectric couples for EMC Nos. 1 and 2 were interchangeable because legs from the same lot and batch were used.

During assembly of thermoelectric couples for EMC No. 2, the concentricity of the leg to the cold cap was out of tolerance. An investigation revealed that the bonding molds used were made of a less dense carbon material than had been specified. New molds were made using the proper material. Thermoelectric couples made with these new molds were all within tolerance.

Thermoelectric cap assemblies (cold cap, jumper wire) were fabricated for EMC No. 3, but bonding of legs to the cap assemblies was postponed pending a decision on whether to use separately segmented P-legs or simultaneous powder press P-legs. The decision was made to use the separately segmented P-legs on EMC No. 3, and these legs were being fabricated at the end of this reporting period.

4.3.2 10-COUPLE MODULE

During the quarter modules 5 through 12 were assembled, modules 5 through 8 were placed on test. Processing was started for modules 9, 11, and 12. Assembly, fabrication and processing were largely accomplished according to plan. Problems encountered along with the corrective action taken are discussed in the following paragraphs.

4.3.2.1 Modules 6 Through 8

The method of instrumenting the hot junctions was changed from that used in modules 1 through 4 because of broken instrumentation wires experienced in modules 1 through 4 as discussed in Quarterly Report No. 3. The diagnostic thermocouple was relocated from the molybdenum hot buttons¹ to the face of the electrode.

¹Alternate hot contact material in test matrix

This method appeared to be satisfactory in exploratory tests, but during final assembly operations (insulation packing) on modules 6 through 8 some of the thermocouple wires became detached. A procedure was worked out to complete the assembly of those modules while still providing the minimum required voltage taps. (Refer to paragraph 4.2.3.1.)

Investigation of a third method (mechanical) was started for application in modules 9-12.

The Conax fittings showed evidence of leakage on all four modules. This was detected in the early stages of processing during a leak integrity check by quality control. They were retightened to 45 inch-pounds (small fittings) and 75 inch-pounds (large fittings). It is believed this problem occurred because of the time lapse between assembly leak checking and start of processing (allowing extensive time for plastic flow). Processing procedures were changed to specify tightening of all Conax fittings immediately prior to processing.

Module 6 had a partially open circuit (the odd circuit). The problem was isolated to the P-1 output leg. Probable cause was a stuck follower. Processing on this unit was finished since it was believed that the circuit loads could still be balanced. Because of this problem, preselected followers will be used on modules 9 through 12 to prevent any follower-hole minimum clearance problems.

The soft solder joint for the pressure gage was melted on module 6 during processing by using an external heat belt to promote rapid rise of heat during the "seat in" period. The module was repaired by reducing the module internal pressure to zero and resoldering the joint. The processing specification was then revised to eliminate the use of external heat.

4.3.2.2 Modules 9 Through 12

Because of instrumentation wire breakage problems, a mechanical means of attaching diagnostic thermocouples to hot junctions was developed prior to assembly of modules 9 through 12. This method consisted of attaching the instrumentation wire to the hot junction electrode by first drilling a small hole through, then drilling a larger hole half way through and weld balling the

instrumentation wire to fit into the larger hole but not the smaller hole, then pulling the wire into the electrode hole and swedging and staking it in position. This method was successfully used on modules 9 through 12.

Final assembly of modules 9 through 12 started early in December and was completed in the middle of the month. No major problems were encountered during final assembly; but, prior to processing, module 10 developed a short circuit and a loss of several instrument wires. Because of this, module 10 will be opened and repaired. It is anticipated that the repair of module 10 will be complete in time to process the unit with Experimental Mockup Converter No. 2 early in the next quarter.

4.4 TEST

4.4.1 POST-TEST ANALYSIS

The prime objective of the SNAP-23 6-couple module A-2 and 252-couple prototype Converter P-1 post-test analysis has been an attempt to clarify or establish potential failure or degrading mechanisms within the converter and module. Both of these devices contain technology developed during the SNAP-23 Program, which is considered as the baseline technology for SNAP-23A.

All analytical efforts on the SNAP-23 post-test analysis were completed during the previous quarter. Findings from these which were included in the Experimental Mockup Converter baseline design were in Quarterly Reports Nos. 2 and 3. Analysis of all data was completed, and the Post-Test Analysis Report (MMM 3824-0002-II of II) was published during the current quarter.

4.4.2 BELL JAR TESTS

Bell jar tests 18-7¹, 16-8, 17/18-9, 8/18-10, 5-11, 9/18-12, 8/18-13 and 11-14 were completed during the quarter. Table 4-1 indicates the leg configurations evaluated and the performance obtained in all the bell jar tests completed thus far. Unless otherwise indicated, nominal leg misalignment was less than

¹18-7 — The first number references the applicable test number as indicated in the bell jar test matrix on page 4-10 of Quarterly Report No. 2 - MMM 3824-0009.

Table 4-1. Bell Jar Test P- and N-Leg Performance Data ($T_h = 1100^\circ\text{F}$,
 $T_c = 190^\circ\text{F}$, 250 psi Contact Pressure, 50-100 Hour Data)

P-Legs	Simultaneously Pressed Conventional						Individually Pressed and Conventional						Simultaneously Pressed Soft Nose						Individually Pressed and Bonded Soft Nose					
	SR		RR		PR		SR		RR		PR		SR		RR		PR		SR		RR		PR	
	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current	Original	Current
Bell Jar Test																								
1-2	0 97	1 01	1 07	1 12	0 88	0 91																		
1-3	0 98	1 02	1 07	1 12	0 90	0 93																		
1 4	0 97	1 01	1 01	1 06	0 93	0 96																		
7/18 5							0 91	0 88	0 71	0 3	1 18	1 06												
							(0 96)	(0 93)	(1 61)	(1 66)	(0 37)	0 2)												
16 6													0 93	0 97	1 03	1 08	0 84	0 87	0 94	0 31	0 77	0 79	1 15	1 05
18 7																			(0 94)	(0 91)	(0 84)	(0 87)	(1 05)	(0 95)
16 8													0 94	0 98	1 10	1 15	0 79	0 83						
17/18 9							0 93	0 90	0 72	0 74	1 20	1 10	(0 92)	(0 96)	(1 10)	(1 15)	(0 77)	(0 81)						
8/18 10*	(0 96)	(1 00)	(2 00)	(2 10)	(0 46)	(0 48)																		
	0 96	1 00	1 35	1 41	0 68	0 71																		
5 11	0 96	1 00	1 03	1 08	0 89	0 92																		
9/18 12**							(0 96)	(0 93)	(1 10)	(1 14)	(0 84)	(0 6)							0 95	0 92	0 84	0 87	1 08	0 9
	(0 97)	(1 01)	(1 16)	(1 21)	(0 81)	(0 81)																		
8/18-13	0 97	1 01	1 10	1 15	0 86	0 89																		
11 14**							0 96	0 93	0 90	0 3	1 02	0												
N Legs																								
1 2	1 01	0 98	0 94	0 93	1 09	1 04																		
1 3	1 02	0 99	0 97	0 96	1 08	1 03																		
1 4	1 03	1 00	1 01	0 99	1 05	1 01																		
7/18 5							1 01	0 98	0 89	0 88	1 15	1 10												
							(1 01)	(0 98)	(0 94)	(0 93)	(1 0)	(1 04)												
16-6	1 02	0 99	0 98	0 96	1 06	1 02	1 01	0 98	0 88	0 87	1 16	1 1												
18 7							1 01	0 98	0 94	0 93	0 9	1 04												
							(1 02)	(0 99)	(0 94)	(0 93)	(1 0)	(1 0)												
16-8	1 00	0 97	0 94	0 93	1 06	1 01																		
17/18 9	1 01	0 98	0 95	0 99	1 07	0 2																		
8/18-10*	1 02	0 99	1 10	1 08	0 93	0 89																		
5-11	1 01	0 98	0 93	0 92	1 09	1 04																		
9/18 12**							1 01	0 98	0 94	0 93	1 08	1 03												
	1 01	0 98	0 89	0 88	1 15	1 10																		
8/18-13	(1 01)	(0 98)	(1 00)	(0 98)	(1 02)	(0 98)																		
11-14**							1 03	1 00	0 97	0 96	1 09	1 04												

*5° Nominal Misalignment
 **2, 5° Nominal Misalignment

SR Seebeck ratio Exper Seebeck voltage
 Theo Seebeck voltage
 RR Resistance ratio Exper resistance
 Theo resistance
 PR Power ratio Exper matched power
 Theo matched power
 () Molybdenum Contact

1/2 degree, and hot contact material was iron. Tests 8/18-10, 9/18-12, and 11-14 had intentional leg misalignment. Test 5-11 utilized Experimental Mockup Converter couples as opposed to the 10-couple module couples used in the other bell jar tests. Observed performance was stable with time except for a slight resistance increase on the molybdenum-contacted P-leg of test 8/18-10.

The "original" performance ratios shown in Table 4-1 use the original¹ thermoelectric materials characterization as a theoretical base. The "current" performance ratios use the latest materials characterization² (refer to paragraph 4.2.2) as a theoretical base. In addition, new performance ratios for bonded type P-legs include revised leg geometry based on a series of actual measurements which indicated a significant difference from nominal design geometry for this type of leg. Similar investigation into the other types of legs used disclosed no significant geometry discrepancy.

Based on a comparison of the data, the results of the tests completed during this quarter are as follows:

Test 18-7: Indicates that molybdenum hot buttons can provide short-term contacting with individually pressed and bonded soft-nost P-legs that is comparable but slightly inferior to that of iron buttons.

Test 16-8: Indicates good correlation and reproducibility relative to the applicable portions of test 16-6.

Test 17/18-9: Correlates well with prior evaluations of similar leg configurations and indicates successful contact of simultaneously pressed soft-nose P-leg with molybdenum hot button.

Test 8/18-10: Indicates initial leg misalignment of 5 degrees is excessive, causing significant internal resistance increases particularly with molybdenum hot contact.

¹SNAP-23 thermoelectric materials characterization values.

²Current SNAP-23A thermoelectric materials characterization values.

Test 5-11: Indicates converter couple performance comparable to other (10-couple module) simultaneously pressed conventional couples.

Test 9/18-12: Indicates initial leg misalignment at 2.5 degrees is excessive for P-legs, causing significant internal resistance increases particularly on the moly-contacted P-leg (contacting with molybdenum generally appears to be difficult).

Test 8/18-13: Correlates fairly well with prior evaluations of similar leg configurations and indicates contact of simultaneously pressed conventional P-leg with molybdenum hot button results in slightly higher resistance than iron contact.

Test 11-14: Indicates initial leg misalignment of 2.5 degrees is excessive for P-leg, causing significant internal resistance increases (20-25%).

4.4.3 10-COUPLE MODULE

Long-term test of modules 1 through 4 continued during the quarter. Long-term test of modules 5 through 8 began during the quarter. Plots of average performance ratios (experimental to theoretical values¹) for modules 1 through 4 are shown in Figures 4-27 through 4-38. Plots for modules 5 through 8 similar to those for modules 1 through 4 (Figures 4-27 through 4-38) are not included in this report since modules 4 through 12 contain a mixture of leg configurations within each module rather than similar types as is the case with modules 1 through 4 (refer to SNAP-23A, 10-Couple Module Variable Matrix, Table 4-1, Quarterly Report No. 1 (MMM 3824-0006)). During the quarter that modules 9 through 12 are placed on long-term test, plots for similar type legs contained in modules 5 through 12 will be made and presented in the quarterly report for that period. The latest experimental data that was normalized² and reduced by

¹Theoretical values used in the 10-couple computer program at this time are the old material characterization coefficients (refer to paragraph 4.2.2).

²Ratios presented in these tables are experimental/theoretical.

the 10-couple module computer program is tabulated for modules 1 through 8 in Tables 4-2 through 4-9 respectively.

The following observations may be noted from Figures 4-1 through 4-12:

N-Legs: N-leg performance appears similar in all four modules; Seebeck ratio is nearly 1.0 and is stable; resistance ratio is nearly 1.0 and is stable or slightly increasing. Differences between types of N-legs are small. Seebeck ratios differ by 1 percent or less. Resistance ratios for bonded type legs are about 4 percent lower than those for simultaneously pressed legs. Performance correlates well with bell jar and EMC No. 1 data.

P-Legs: The simultaneously pressed P-leg resistance ratios exhibit considerable increase with time (from an initial high value). In modules 2, 3, and 4, which contain either Microquartz or Min-K 1999 insulation, the resistance ratios are still continuing to increase. However, in Module 1, the resistance ratio increased approximately 10 percent from its initial value over the first 700 hours, but appears to be decreasing slightly since that time. It is significant to note that Module 1 (with Min-K 1301 insulation and simultaneously pressed, conventional P-legs) exhibits performance similar to that shown with SNAP-23 Converter P-1 which was the base from which the EMC has been designed. (Refer to paragraph 3.2.3 for EMC No. 1 performance information and discussion.)

The separately pressed and bonded P-legs in all four modules exhibit initial decrease of resistance ratio for approximately 700 hours, but this parameter then appears to increase slightly thereafter. All four modules indicate approximately the same level of resistance ratio.

By comparison between resistance ratios for Modules 2 and 4, no significant difference is exhibited between conventional and soft

nose couples; however, different contact pressures are used (250 psi for conventional, 150 psi for soft nose). For all modules, Seebeck voltage ratios for simultaneously pressed P-legs exhibit similar performance with approximately a 3 percent increase during the first 1500 hours.

The power ratios for the four modules show the combined effects of Seebeck voltage and resistance changes described. It may be observed that the power ratio for Module No. 1 appears to be relatively stable over the last 1400 hours for both simultaneously pressed and bonded P-legs. Again, this exhibits performance similar to that shown with the baseline SNAP-23 converter P-1.

4.4.4 SNAP-23 CONTINUATION TESTING

4.4.4.1 Introduction

During the SNAP-23 Program (Contract AT(30-1) 3418), 3M designed, developed, fabricated, and tested two full-scale 60-watt thermoelectric converters and two six-couple modules. The thermoelectric materials system, type of leg construction, and converter design details formed the basis for the follow-on SNAP-23A converter development and technology program.

Thermoelectric converter 39P-1 and six-couple module 39A-2 were disassembled for the SNAP-23A post-test analysis effort. Six-couple module 39A-3 has continued on long-term test. Thermoelectric converter 39P-2 will be placed back on long-term test upon completion of heat source simulator rework.

This continuation test effort has been transferred to the SNAP-23A Test Program.

4.4.4.2 Module A-3

Long-term test of SNAP-23 six-couple Module A-3 continued during the quarter. Performance data for the module is summarized in Table 4-10 and shown graphically in Figure 4-39.

Nomenclature for Table 4-10 and Figure 4-39 is as follows: In this table and graph, the following nomenclature is used:

- T_h - Average hot electrode temperature ($^{\circ}\text{F}$)
- T_c - Average cold electrode temperature ($^{\circ}\text{F}$)
- E_x - Experimental open circuit voltage (volts)
- I_x - Experimental load current (amps)
- R_x - Experimental internal resistance (ohms)
- P_x - Experimental power-to-load (watts)

The long-term testing of module A-3 has continued without interruption for approximately 25,000 hours. The module exhibited about a 10-percent increase in internal resistance (almost entirely P-leg based) within the first 1000 hours of operation, but has shown relative long-term stability since that time, with a gradual decrease in both resistance and open circuit voltage and consequent decrease in power delivered to the load.

4.4.4.3 Converter P-2

Several unsuccessful approaches for removal of the heat source material from converter P-2 were attempted during the last quarter as described in Quarterly Report No. 3 (MMM 3824-0013). During this quarter, an engineering plan was drawn for the removal of the heat source material from the converter and the placing of the converter back on long term performance test. The heat source and fin radiator were successfully separated from the converter without damage to the converter, and initial refurbishing operations were started. Disposition instructions for the radiation shield were also requested from the AEC.

Table 4-2. Ten-Couple Module Analysis-23A Module
Number 1 - 2143 Hours

LEG	SEEBECK VOLTAGE			LEG PARAMETERS		RESISTANCE RATIO
	EXP (MV)	NORM (MV)	RATIO *	EXP (M-OHM)	NORM (M-OHM)	
1P	102.00	102.33	1.04	18.67	18.62	1.20
1N	114.00	114.24	1.05	18.33	18.21	1.00
3P	103.00	103.20	1.05	18.33	18.27	1.18
3N	115.00	113.83	1.05	18.00	18.39	1.01
5P	103.00	101.69	1.04	18.00	18.15	1.17
5N	114.00	113.18	1.04	19.33	19.68	1.09
7P	103.00	100.67	1.02	17.67	17.63	1.14
7N	116.00	113.88	1.05	18.00	18.05	1.00
9P	101.00	101.77	1.04	18.00	18.32	1.18
9N	114.00	115.05	1.06	17.67	18.26	1.01
2P	97.00	95.51	0.97	12.00	11.93	0.77
2N	115.00	113.44	1.05	18.00	17.90	0.99
4P	94.00	93.62	0.95	12.33	12.36	0.80
4N	118.00	116.73	1.08	17.67	18.16	1.00
6P	100.00	98.22	1.00	12.33	12.44	0.80
6N	114.00	112.91	1.04	17.33	17.60	0.97
8P	98.00	96.88	0.99	13.00	13.07	0.84
8N	115.00	114.04	1.05	17.67	17.96	0.99
10P	97.00	96.01	0.98	13.00	13.09	0.85
10N	115.00	114.18	1.05	18.00	18.32	1.01

LEG	EXP (MW)	POWER NORM (MW)	RATIO
1P	138.00	140.62	0.89
1N	177.00	179.23	1.10
3P	144.00	145.74	0.93
3N	183.00	176.18	1.06
5P	147.00	142.41	0.91
5N	168.00	162.75	1.00
7P	150.00	143.69	0.92
7N	186.00	179.60	1.10
9P	141.00	141.35	0.90
9N	183.00	181.20	1.11
2P	183.00	191.08	1.14
2N	183.00	179.75	1.10
4P	171.00	177.29	1.09
4N	195.00	187.58	1.14
6P	189.00	193.88	1.16
6N	186.00	181.14	1.11
8P	177.00	179.48	1.10
8N	186.00	181.05	1.11
10P	174.00	176.13	1.09
10N	183.00	177.88	1.09

COUPLE	SEEBECK VOLTAGE			COUPLE PARAMETERS			POWER		
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1	216.00	216.57	1.05	37.00	36.82	1.10	315.00	319.84	1.00
3	218.00	217.03	1.05	36.33	36.66	1.09	327.00	321.92	1.01
5	217.00	214.87	1.04	37.33	37.83	1.13	315.00	305.16	0.96
7	219.00	214.54	1.04	35.67	35.68	1.06	336.00	323.29	1.01
9	215.00	216.81	1.05	35.67	36.58	1.09	324.00	322.55	1.01
2	212.00	208.95	1.01	30.00	29.83	0.89	366.00	370.83	1.12
4	212.00	210.36	1.02	30.00	30.52	0.91	366.00	364.87	1.12
6	214.00	211.13	1.02	29.67	30.04	0.89	375.00	375.01	1.13
8	213.00	210.92	1.02	30.67	31.03	0.92	363.00	360.52	1.11
10	212.00	210.19	1.02	31.00	31.41	0.93	357.00	354.02	1.09

*Ratios in these analyses are experimental/theoretical

Figure 4-27. Seebeck Voltage Ratio vs Elapsed Time (Module 1)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-28. Resistance Ratio vs Elapsed Time (Module 1)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-29. Power Ratio vs Elapsed Time (Module 1)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Table 4-3. Ten-Couple Module Analysis-23A Module
Number 2 - 2118 Hours

LEG PARAMETERS									
LEG	SEEBECK VOLTAGE			RATIO	RESISTANCE		RATIO		
	EXP (MV)	NORM (MV)			EXP (M-OHM)	NORM (M-OHM)			
1P	98.00	100.27		1.02	23.00	22.96	1.48		
1N	113.00	115.10		1.06	19.00	18.75	1.04		
3P	94.00	96.05		0.98	21.00	20.94	1.35		
3N	113.00	113.63		1.05	18.00	18.28	1.01		
5P	95.00	95.23		0.97	24.00	24.16	1.56		
5N	113.00	114.45		1.06	18.67	18.44	1.02		
7P	97.00	98.97		1.01	23.00	23.00	1.49		
7N	113.00	112.80		1.04	16.67	17.34	0.96		
9P	97.00	95.55		0.97	24.00	24.28	1.57		
9N	115.00	113.83		1.05	18.33	18.90	1.04		
2P	91.00	90.75		0.92	12.67	12.71	0.82		
2N	114.00	113.81		1.05	17.33	17.46	0.96		
4P	93.00	92.27		0.94	13.00	12.99	0.84		
4N	113.00	112.06		1.03	17.67	17.79	0.98		
6P	93.00	92.78		0.94	13.33	13.43	0.87		
6N	114.00	113.71		1.05	17.33	17.69	0.98		
8P	93.00	91.43		0.93	13.33	13.34	0.86		
8N	114.00	112.18		1.03	16.67	16.91	0.93		
10P	91.00	89.72		0.91	12.67	12.76	0.82		
10N	114.00	112.84		1.04	17.67	18.05	1.00		
LEG	POWER			RATIO				RATIO	
	EXP (MW)	NORM (MW)							
1P	87.00	109.49		0.59					
1N	168.00	176.61		1.09					
3P	93.00	110.13		0.62					
3N	177.00	176.61		1.09					
5P	69.00	93.86		0.44					
5N	171.00	177.55		1.09					
7P	84.00	106.47		0.56					
7N	189.00	183.40		1.12					
9P	75.00	93.99		0.46					
9N	180.00	171.38		1.05					
2P	159.00	162.06		1.01					
2N	186.00	185.42		1.13					
4P	162.00	163.79		1.02					
4N	180.00	176.44		1.08					
6P	159.00	160.28		1.01					
6N	186.00	182.71		1.12					
8P	159.00	156.63		0.99					
8N	192.00	185.59		1.13					
10P	159.00	157.70		0.98					
10N	183.00	176.39		1.08					
COUPLE PARAMETERS									
COUPLE	SEEBECK VOLTAGE			RESISTANCE			POWER		
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1	211.00	215.36	1.04	42.00	41.71	1.24	255.00	286.10	0.84
3	207.00	209.68	1.02	39.00	39.22	1.17	270.00	286.74	0.87
5	208.00	209.68	1.01	42.67	42.60	1.27	240.00	271.40	0.77
7	210.00	211.76	1.02	39.67	40.34	1.21	273.00	289.87	0.86
9	212.00	209.39	1.01	42.33	43.19	1.29	255.00	265.38	0.77
2	205.00	204.56	0.99	30.00	30.17	0.90	345.00	347.48	1.07
4	206.00	204.33	0.99	30.67	30.79	0.92	342.00	340.23	1.05
6	207.00	206.49	1.00	30.67	31.12	0.93	345.00	342.99	1.06
8	207.00	203.61	0.99	30.00	30.26	0.90	351.00	342.63	1.06
10	205.00	202.57	0.98	30.33	30.81	0.92	342.00	334.09	1.03

Figure 4-30. Seebeck Voltage Ratio vs Elapsed Time (Module 2)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-31. Resistance Ratio vs Elapsed Time (Module 2)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-32. Power Ratio vs Elapsed Time (Module 2)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Table 4-4. Ten-Couple Module Analysis-23A Module
Number 3 - 2093 Hours

LEG PARAMETERS									
LEG	SEEBECK VOLTAGE			RESISTANCE		RATIO			
	EXP (MV)	NORM (MV)	RATIO	EXP (M-OHM)	NORM (M-OHM)				
1P	98.00	98.82	1.01	25.00	25.08	1.02			
1N	112.00	112.62	1.04	19.00	19.06	1.05			
3P	99.00	99.96	1.02	24.33	24.43	1.58			
3N	113.00	113.05	1.04	18.67	19.16	1.06			
5P	100.00	99.93	1.02	24.33	24.65	1.59			
5N	113.00	112.77	1.04	19.00	19.72	1.09			
7P	99.00	97.40	0.99	24.00	24.23	1.57			
7N	114.00	113.16	1.04	18.67	18.95	1.05			
9P	99.00	97.37	0.99	25.00	25.03	1.62			
9N	114.00	112.49	1.04	18.67	18.83	1.04			
2P	94.00	94.48	0.96	12.33	12.42	0.80			
2N	112.00	112.61	1.04	17.67	17.89	0.99			
4P	93.00	93.35	0.95	13.00	13.08	0.85			
4N	114.00	115.13	1.06	18.67	18.60	1.03			
6P	92.00	93.35	0.95	12.33	12.36	0.80			
6N	113.00	113.54	1.05	17.67	18.01	0.99			
8P	94.00	94.10	0.96	13.00	13.11	0.85			
8N	112.00	112.05	1.03	17.33	17.71	0.98			
10P	95.00	93.88	0.96	12.67	12.70	0.82			
10N	115.00	113.95	1.05	17.00	17.19	0.95			
LEG	POWER			RESISTANCE		RATIO			
	EXP (MW)	NORM (MW)	RATIO	EXP (M-OHM)	NORM (M-OHM)				
1P	69.00	97.35	0.45						
1N	165.00	166.95	1.03						
3P	78.00	102.24	0.51						
3N	171.00	166.76	1.03						
5P	81.00	101.27	0.51						
5N	168.00	161.22	0.99						
7P	81.00	97.87	0.50						
7N	174.00	168.92	1.04						
9P	72.00	94.72	0.45						
9N	174.00	168.02	1.04						
2P	171.00	179.66	1.10						
2N	177.00	177.15	1.09						
4P	162.00	166.55	1.04						
4N	174.00	178.13	1.10						
6P	165.00	176.22	1.09						
6N	180.00	178.97	1.10						
8P	165.00	168.93	1.05						
8N	180.00	177.25	1.09						
10P	171.00	173.43	1.07						
10N	192.00	188.89	1.15						
COUPLE PARAMETERS									
COUPLE	SEEBECK VOLTAGE			RESISTANCE		POWER			
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1	210.00	211.64	1.02	44.00	44.14	1.31	234.00	264.29	0.74
3	212.00	213.00	1.03	43.00	43.59	1.30	249.00	269.00	0.78
5	213.00	212.70	1.03	43.33	44.37	1.32	249.00	262.48	0.76
7	213.00	210.56	1.02	42.67	43.19	1.29	255.00	266.79	0.77
9	213.00	209.86	1.02	43.67	43.85	1.31	246.00	262.74	0.75
2	206.00	207.08	1.00	30.00	30.32	0.90	348.00	356.81	1.09
4	207.00	208.49	1.01	31.67	31.68	0.94	336.00	344.68	1.07
6	205.00	206.89	1.00	30.00	30.37	0.90	345.00	355.19	1.09
8	206.00	206.15	1.00	30.33	30.81	0.92	345.00	346.18	1.07
10	210.00	207.83	1.01	29.67	29.89	0.89	363.00	362.32	1.11

Figure 4-33. Seebeck Voltage Ratio vs Elapsed Time (Module 3)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-34. Resistance Ratio vs Elapsed Time (Module 3)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-35. Power Ratio vs Elapsed Time (Module 3)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Table 4-5. Ten-Couple Module Analysis-23A Module
Number 4- 2069 Hours

TEN COUPLE MODULE ANALYSIS-23A
MODULE NUMBER 4- 2069 HOURS

LEG	SEEBECK VOLTAGE			LEG PARAMETERS		RESISTANCE RATIO
	EXP (MV)	NORM (MV)	RATIO	EXP (M-OHM)	NORM (M-OHM)	
1P	99.00	100.42	1.02	22.67	22.44	1.45
1N	112.00	113.11	1.04	20.00	19.47	1.7
3P	95.00	96.36	0.98	24.00	23.76	1.54
3N	115.00	113.36	1.05	19.00	19.73	1.09
5P	96.00	93.68	0.95	21.67	21.92	1.42
5N	114.00	113.40	1.05	19.00	18.98	1.05
7P	97.00	95.80	0.98	23.33	23.20	1.5
7N	115.00	113.03	1.04	18.33	18.49	1.2
9P	96.00	94.94	0.97	23.00	23.16	1.5
9N	116.00	115.10	1.06	18.33	18.69	1.53
2P	91.00	92.38	0.94	11.00	10.92	.71
2N	110.00	111.22	1.03	19.67	19.26	1.6
4P	89.00	91.42	0.93	11.33	11.34	.71
4N	115.00	114.26	1.05	17.67	18.89	1.4
6P	93.00	90.99	0.93	11.33	11.61	.75
6N	113.00	112.46	1.04	16.67	17.25	.95
8P	92.00	91.17	0.93	12.67	12.85	.83
8N	116.00	115.65	1.07	19.67	20.25	1.12
10P	93.00	91.12	0.93	12.33	12.37	.8
10N	115.00	113.16	1.04	16.67	16.91	.75

LEG	POWER		RATIO
	EXP (MW)	NORM (MW)	
1P	93.00	112.35	0.62
1N	156.00	164.26	1.01
3P	69.00	97.71	0.46
3N	174.00	162.87	1.00
5P	93.00	100.12	0.56
5N	171.00	169.39	1.04
7P	81.00	98.91	0.51
7N	180.00	172.68	1.06
9P	81.00	97.28	0.50
9N	183.00	177.19	1.09
2P	174.00	195.32	1.16
2N	153.00	160.56	0.98
4P	165.00	184.24	1.12
4N	186.00	172.77	1.06
6P	177.00	178.26	1.06
6N	189.00	183.32	1.12
8P	162.00	161.67	1.01
8N	171.00	165.13	1.02
10P	163.00	167.74	1.03
10N	195.00	189.27	1.15

COUPLE	SEEBECK VOLTAGE			COUPLE PARAMETERS			POWER		
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1	211.00	213.53	1.03	42.67	41.91	1.25	249.00	276.61	0.82
3	210.00	205.73	1.02	43.00	43.49	1.30	243.00	260.58	0.75
5	210.00	207.09	1.00	40.67	40.90	1.22	264.00	269.51	0.80
7	212.00	208.83	1.01	41.67	41.69	1.24	261.00	271.59	0.80
9	212.00	210.04	1.02	41.33	41.86	1.25	264.00	274.47	0.87
2	201.00	203.59	0.99	30.67	30.18	0.90	327.00	355.88	1.07
4	204.00	205.68	1.00	29.00	30.23	0.89	351.00	357.02	1.08
6	206.00	203.45	0.98	28.00	28.86	0.86	366.00	361.58	1.09
8	208.00	206.83	1.00	32.33	33.10	0.98	333.00	326.80	1.01
10	208.00	204.27	0.99	29.00	29.29	0.87	363.00	357.01	1.09

Figure 4-36. Seebeck Voltage Ratio vs Elapsed Time (Module 4)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-37. Resistance Ratio vs Elapsed Time (Module 4)

$$\text{Ratio} = R_{\text{Experimental}} / R_{\text{Theoretical}}$$

Figure 4-38. Power Ratio vs Elapsed Time (Module 4)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Table 4-6. Ten-Couple Module Analysis-23A Module
Number 5- 533 Hours

LEG PARAMETERS									
LEG	SEEBECK VOLTAGE			RESISTANCE		RATIO			
	EXP (MV)	NORM (MV)	RATIO	EXP (M-OHM)	NORM (M-OHM)				
1P *				107.17	106.20	7.57			
1N	98.00	99.10	1.04	16.23	15.85	1.00			
3P	79.00	80.06	0.94	10.94	10.83	0.77			
3N	99.00	98.43	1.04	16.98	17.18	1.08			
5P	84.00	83.36	0.98	24.91	25.01	1.78			
5N	98.00	99.10	1.04	16.60	16.14	1.01			
7P	85.00	86.32	1.01	20.75	20.52	1.46			
7N	99.00	96.58	1.04	15.85	15.98	1.00			
9P	84.00	83.40	0.98	20.00	20.04	1.43			
9N	100.00	99.43	1.05	16.60	16.72	1.05			
2P	79.00	79.78	0.94	18.67	18.56	1.32			
2N	98.00	98.73	1.04	16.00	15.76	0.99			
4P	74.00	74.73	0.88	16.33	16.24	1.16			
4N	98.00	98.80	1.04	15.00	14.75	0.93			
6P	77.00	78.08	0.92	11.00	10.95	0.78			
6N	99.00	99.21	1.04	17.33	17.45	1.10			
8P	78.00	77.91	0.91	13.33	13.36	0.99			
8N	100.00	99.86	1.05	16.33	16.43	1.03			
10P	83.00	82.57	0.97	20.00	20.01	1.43			
10N	101.00	100.57	1.06	16.67	16.72	1.05			
LEG	EXP (MW)	POWER NORM (MW)	RATIO						
1P *									
1N	145.75	154.93	1.07						
3P	132.50	147.93	1.06						
3N	143.10	141.00	0.98						
5P	47.70	89.45	0.36						
5N	143.10	152.16	1.06						
7P	79.50	90.79	0.64						
7N	151.05	152.04	1.05						
9P	82.15	86.78	0.62						
9N	148.40	147.84	1.03						
2P	69.00	85.72	0.55						
2N	150.00	154.59	1.09						
4P	75.00	85.96	0.59						
4N	159.00	165.44	1.16						
6P	132.00	139.13	1.05						
6N	141.00	141.01	0.99						
8P	114.00	113.58	0.88						
8N	153.00	151.72	1.07						
10P	69.00	85.17	0.53						
10N	153.00	151.20	1.06						
SEEBECK VOLTAGE				COUPLE PARAMETERS		POWER			
COUPLE	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1 *									
3	178.00	178.49	0.99	27.92	28.01	0.93	275.60	288.93	1.02
5	182.00	182.47	1.01	41.51	41.15	1.37	190.80	221.61	0.71
7	184.00	184.89	1.03	36.60	36.49	1.22	230.55	242.83	0.86
9	184.00	182.83	1.01	36.60	36.76	1.23	230.55	234.62	0.83
2	177.00	178.50	0.99	34.67	34.32	1.15	219.00	240.31	0.83
4	172.00	173.52	0.96	31.33	30.99	1.03	234.00	251.40	0.89
6	176.00	177.29	0.98	28.33	28.40	0.95	273.00	280.14	1.02
8	178.00	177.76	0.99	29.67	29.79	0.99	267.00	265.30	0.98
10	184.00	183.14	1.02	36.67	36.73	1.23	222.00	236.38	0.81
* NO VALID DATA AVAILABLE									

* NO VALID DATA AVAILABLE

Table 4-7. Ten-Couple Module Analysis-23A Module
Number 6- 533 Hours

LEG	SEEBECK VOLTAGE			LEG PARAMETERS		RESISTANCE RATIO
	EXP (MV)	NORM (MV)	RATIO	EXP (M-OHM)	NORM (M-OHM)	
1P *						
1N *						
3P	97.00	98.27	1.00	22.67	22.87	1.48
3N	113.00	113.18	1.04	17.67	18.41	1.02
5P	93.00	92.80	0.94	12.33	12.58	0.81
5N	113.00	114.83	1.06	17.67	17.72	0.98
7P	92.00	93.60	0.95	14.00	14.06	0.91
7N	112.00	112.32	1.04	17.67	18.26	1.01
9P	97.00	97.01	0.99	22.00	22.36	1.44
9N	113.00	113.32	1.05	18.33	18.95	1.05
2P	94.00	94.43	0.96	12.33	12.49	0.81
2N	112.00	112.67	1.04	17.67	18.11	1.00
4P	88.00	88.40	0.90	19.33	19.58	1.27
4N	112.00	113.67	1.05	17.67	17.70	0.98
6P	92.00	93.60	0.95	15.00	15.06	0.97
6N	112.00	112.53	1.04	17.00	17.49	0.97
8P	96.00	96.26	0.98	27.33	27.72	1.79
8N	112.00	112.11	1.03	17.00	17.66	0.97
10P	97.00	96.50	0.98	25.33	25.75	1.66
10N	113.00	112.64	1.04	18.00	18.65	1.03

LEG	EXP (MW)	POWER NORM (MW)	RATIO
1P *			
1N *			
3P	87.00	105.59	0.57
3N	180.00	173.96	1.07
5P	168.00	171.22	1.05
5N	180.00	186.00	1.14
7P	150.00	155.79	0.99
7N	177.00	172.68	1.06
9P	93.00	105.24	0.59
9N	174.00	169.38	1.04
2P	171.00	178.43	1.09
2N	177.00	175.19	1.08
4P	90.00	99.76	0.58
4N	177.00	182.51	1.12
6P	141.00	145.40	0.93
6N	183.00	181.01	1.11
8P	42.00	83.57	0.27
8N	183.00	177.91	1.09
10P	63.00	90.43	0.39
10N	177.00	170.66	1.05

COUPLE	SEEBECK VOLTAGE			COUPLE PARAMETERS			POWER		
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM	RATIO
1 *									
3	210.00	211.46	1.02	40.33	41.28	1.23	267.00	279.55	0.83
5	206.00	207.63	1.00	30.00	30.30	0.90	348.00	357.21	1.10
7	204.00	205.92	1.00	31.67	32.32	0.96	327.00	328.46	1.03
9	210.00	210.33	1.02	40.33	41.31	1.23	267.00	274.62	0.82
2	206.00	207.09	1.00	30.00	30.61	0.91	348.00	353.61	1.08
4	200.00	202.07	0.98	37.00	37.28	1.11	267.00	282.26	0.85
6	204.00	206.12	1.00	32.00	32.55	0.97	324.00	326.41	1.02
8	208.00	208.38	1.01	44.33	45.39	1.36	225.00	261.48	0.69
10	210.00	209.35	1.01	43.33	44.40	1.32	240.00	261.10	0.73

* NO VALID DATA AVAILABLE

Table 4-8. Ten-Couple Module Analysis-23A Module
Number 7- 529 Hours

LEG PARAMETERS						
LEG	SEEBECK VOLTAGE			RESISTANCE		RATIO
	EXP (MV)	NORM (MV)	RATIO	EXP (M-OHM)	NORM (M-OHM)	
1P	81.00	79.79	0.94	10.33	10.30	0.73
1N	99.00	97.72	1.03	15.67	15.67	0.98
3P	86.00	84.72	0.99	20.67	20.59	1.47
3N	98.00	96.60	1.02	16.33	16.39	1.03
5P	77.00	75.82	0.89	10.67	10.65	0.76
5N	98.00	97.01	1.02	15.33	15.30	0.96
7P	78.00	77.22	0.91	11.33	11.30	0.81
7N	99.00	97.65	1.03	15.33	15.51	0.97
9P	85.00	83.58	0.98	22.00	22.04	1.57
9N	101.00	99.62	1.05	16.33	16.52	1.04
2P	84.00	82.92	0.97	20.00	19.98	1.42
2N	98.00	96.94	1.02	16.00	16.07	1.01
4P	83.00	82.30	0.96	19.00	19.05	1.36
4N	99.00	99.95	1.05	17.67	17.14	1.08
6P	78.00	78.70	0.92	12.00	11.81	0.84
6N	98.00	96.87	1.02	15.67	15.76	0.99
8P	86.00	84.81	0.99	19.67	19.66	1.40
8N	100.00	99.13	1.04	17.00	16.99	1.07
10P	78.00	76.99	0.90	17.67	17.58	1.25
10N	101.00	99.84	1.05	16.33	16.28	1.02

LEG	POWER		
	EXP (MW)	NORM (MW)	RATIO
1P	150.00	154.60	1.13
1N	156.00	152.36	1.07
3P	72.00	87.14	0.54
3N	147.00	142.30	1.00
5P	135.00	134.89	1.01
5N	156.00	153.74	1.08
7P	132.00	131.92	1.00
7N	159.00	153.71	1.08
9P	57.00	79.23	0.42
9N	156.00	150.18	1.06
2P	72.00	86.01	0.54
2N	150.00	146.17	1.03
4P	78.00	88.92	0.59
4N	138.00	145.66	1.02
6P	126.00	131.12	1.01
6N	153.00	148.81	1.05
8P	81.00	91.44	0.61
8N	147.00	144.61	1.02
10P	75.00	84.29	0.57
10N	156.00	153.07	1.08

COUPLE PARAMETERS								
COUPLE	SEEBECK VOLTAGE			RESISTANCE			POWER	
	EXP	NORM	RATIO	EXP	NORM	RATIO	EXP	NORM
1	180.00	177.51	0.98	26.00	25.96	0.87	306.00	306.96
3	184.00	181.31	1.01	37.00	36.98	1.24	219.00	229.44
5	175.00	172.83	0.96	26.00	25.96	0.87	291.00	288.64
7	177.00	174.87	0.97	26.67	26.81	0.89	291.00	285.62
9	186.00	183.20	1.02	38.33	38.56	1.29	213.00	229.41
2	182.00	175.85	1.00	36.00	36.06	1.20	222.00	232.18
4	182.00	182.25	1.01	36.67	36.19	1.21	216.00	234.58
6	176.00	175.57	0.97	27.67	27.57	0.92	279.00	279.93
8	186.00	183.94	1.02	36.67	36.65	1.22	228.00	236.05
10	179.00	176.82	0.98	34.00	33.86	1.13	231.00	237.36

Table 4-9. Ten-Couple Module Analysis-23A Module
Number 8- 528 Hours

LEG PARAMETERS			
SEEBECK VOLTAGE			RATIO
LEG	EXP (MV)	NORM (MV)	
1P	95.00	99.29	1.01
1N	110.00	113.72	1.05
3P	93.00	96.94	0.99
3N	113.00	113.62	1.05
5P	96.00	96.54	0.98
5N	112.00	113.11	1.04
7P	92.00	93.11	0.95
7N	113.00	114.05	1.05
9P	94.00	94.92	0.97
9N	114.00	114.92	1.06
2P *			
2N *			
4P	86.00	87.36	0.89
4N	113.00	113.33	1.05
6P	91.00	91.42	0.93
6N	112.00	112.81	1.04
8P	90.00	90.42	0.92
8N	114.00	114.55	1.06
10P	95.00	95.32	0.97
10N	115.00	115.41	1.06
LEG	EXP (MW)	POWER NORM (MW)	RATIO
1P	24.00	86.39	0.17
1N	159.00	179.24	1.10
3P	33.00	87.52	0.23
3N	174.00	174.55	1.08
5P	87.00	103.81	0.56
5N	174.00	178.30	1.10
7P	168.00	180.48	1.10
7N	174.00	177.68	1.09
9P	87.00	103.92	0.57
9N	168.00	171.29	1.06
2P *			
2N *			
4P	144.00	150.89	0.95
4N	177.00	175.77	1.08
6P	174.00	188.20	1.12
6N	183.00	184.84	1.13
8P	147.00	148.73	0.95
8N	177.00	177.18	1.09
10P	102.00	111.19	0.66
10N	177.00	176.88	1.09
COUPLE PARAMETERS			
SEEBECK VOLTAGE			RATIO
COUPLE	EXP	NORM	
1	205.00	213.01	1.03
3	206.00	210.55	1.02
5	208.00	209.65	1.01
7	205.00	207.16	1.00
9	208.00	209.84	1.02
2 *			
4	199.00	200.69	0.97
6	203.00	204.23	0.99
8	204.00	204.97	0.99
10	210.00	210.74	1.02
RESISTANCE			RATIO
COUPLE	EXP	NORM	
1	48.00	46.57	1.38
3	45.67	45.33	1.35
5	40.33	40.38	1.20
7	30.33	30.31	0.90
9	41.00	40.95	1.22
2 *			
4	30.67	30.91	0.92
6	28.00	28.31	0.84
8	32.00	32.26	0.96
10	39.00	39.26	1.17
POWER			RATIO
COUPLE	EXP	NORM	
1	183.00	265.62	0.64
3	207.00	262.11	0.68
5	261.00	282.11	0.83
7	342.00	358.16	1.10
9	255.00	275.21	0.82
2 *			
4	321.00	326.65	1.02
6	357.00	373.04	1.12
8	324.00	325.91	1.02
10	279.00	288.07	0.88

* NO VALID DATA AVAILABLE

Table 4-10. SNAP-23 Six-Couple Module A3 Performance Data
(Start of test: 3/5/65; current reading: 12/18/67)

Hours	T _h [*] (°F)	T _c (°F)	E _x (volt)	I _x (amp)	R _x (ohm)	P _x (watt)
70	1102	190	1.26	2.84	0.23	1.75
166	1103	196	1.26	2.76	0.24	1.64
454	1104	197	1.27	2.58	0.25	1.62
1,010	1100	194	1.28	2.55	0.26	1.57
1,630	1100	197	1.28	2.64	0.26	1.57
2,130	1100	189	1.29	2.66	0.26	1.59
2,490	1100	192	1.28	2.65	0.26	1.58
3,000	1100	190	1.28	2.50	0.26	1.61
4,120	1100	191	1.28	2.60	0.26	1.60
5,010	1100	191	1.27	2.58	0.26	1.58
5,520	1100	186	1.27	2.57	0.26	1.57
6,020	1100	191	1.26	2.54	0.26	1.54
7,150	1100	197	1.25	2.51	0.26	1.52
8,180	1090	197	1.22	2.44	0.26	1.47
8,900	1090	190	1.22	2.46	0.26	1.46
10,130	1085	189	1.22	2.45	0.25	1.46
11,230	1100	190	1.23	2.48	0.26	1.50
12,600	1100	192	1.23	2.50	0.25	1.52
14,910	1076	190	1.18	2.37	0.25	1.42
17,710	1095	193	1.20	2.35	0.24	1.47
20,160	1100	195	1.18	2.36	0.24	1.43
22,630	1100	193	1.17	2.33	0.24	1.42
23,688	1095	190	1.17	2.36	0.24	1.43
25,128	1100	192	1.17	2.34	0.24	1.41

*All T_h parameters after the 166-hour point were established on the basis of Seebeck voltage.

NOMENCLATURE

P - Power Delivered to Load
 E - Open Circuit Voltage
 R - Internal Resistance

T_h Avg = 1070°F
 T_c Avg = 200°F

Figure 4-39. SNAP-23 Performance Data — Module A3

In determining the disassembly technique used, the status of the P-2 was reviewed, and the end use (bench-top test vehicle) was considered. The heat source was separated from converter P-2 by first cutting the insulation cover with an acetylene torch. Cutting was accomplished as described below:

1. A circular cut was taken at a diameter larger than the fin assembly. This allowed the insulation between the cover and insulating system to be removed and the remaining part of the cover to drop away. The converter was not affected by the cutting torch.
2. Two radial cuts on the remaining portion of the cover exposed the top part of the copper accumulator.

Once the accumulator was exposed, it was cut with a saw through the diameter and the cross hole provided for heater leads. Instrumentation leads were then cut and tagged, and the fin structure removed. The converter was then mounted in a milling machine upside-down and clamped into place with a firm support on the spud. The exposed section of the spud was then milled off and a 1/2-inch hole was drilled vertically through the spud to provide a good interface surface.

Additional effort to be performed before final assembly of the converter to the test fixture includes fabrication of the heater block, bench-top support base, heater block and heating spud to support base tie-in hardware, modification of the test panel and test panel wiring, and cleaning of the converter and radiator fin base of heat transfer grease.

4.5 QUALITY ASSURANCE

4.5.1 QUALITY CONTROL

No major problems were encountered during building of modules 5 through 8 and 9, 11 and 12. All departures were documented with the appropriate disposition obtained for each. Preliminary data indicates module 10 has a short, and investigation has been initiated to isolate the cause.

4.5.2 RELIABILITY

Assembly of modules 5 through 12 and long-term tests of modules 1 through 4 were monitored for reliability assurance. The performance data accumulated to date is not sufficient for a final reliability prediction. Although performance is deviating from the predicated values, the significance is not yet analyzable on a life-time basis.

SECTION 5.0

TASK IV-25- AND 100-WATT CONCEPTUAL DESIGN

SECTION 5.0
TASK IV-25- AND 100-WATT CONCEPTUAL DESIGN

No effort was expended on this task during the reporting period.